2015

Cathodic Protection for Reinforced Concrete Structures: Present Practice and Moves Toward using Renewable Energy

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Recommended Citation

Byrne, A., Holmes, N., & Norton, B. (2015) Cathodic Protection for Reinforced Concrete Structures: present practice and moves toward using renewable energy, *Corrosion Science,* 2015

Elsevier Editorial System(tm) for Corrosion Science
Manuscript Draft

Manuscript Number:

Title: Cathodic Protection for Reinforced Concrete Structures: present practice and moves toward using renewable energy

Article Type: Review Article

Keywords: A. Concrete
A. Steel
A. Steel Reinforced Concrete
C. Cathodic Protection
C. Repassivation
C. Rust

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Abstract: Cathodic protection (CP) limits the corrosion of a metal by making it the cathode of an electrochemical cell. This is achieved either by (i) using more active sacrificial anodes to create a driving current, or (ii) using inert anodes and impressing an external direct current (DC). This paper presents up-to-date CP systems available for reinforced concrete, particularly Impressed Current Cathodic Protection (ICCP) and self-sufficient or renewable energy systems. The potential for overcoming the mismatch in energy provision from renewable sources (intermittent current) with energy needs for CP (constant current) is discussed by exploring novel designs and examining current requirements.

January 2015
Corrosion Science,
Elsevier Publishing.

Dear Editor-in-Chief G. T. Burnstein,

Attached is a review article that I hope to publish in your esteemed journal. I am the corresponding author and have written the paper with commentary and suggestions from Dr. Niall Holmes, and the President of Dublin Institute of Technology, Prof. Brian Norton. My last published paper was [1] and I have no concurrent papers at the time of submission. This is part of a Science Foundation Ireland (SFI) Technology Innovation Development Awarded (TIDA) project, however, SFI have not had any input into directing the research or this paper.

If accepted, this would be the first review article to examine the *cathodic protection of reinforced concrete structures*. Cathodic protection is designed to mitigate corrosion. While there has been reasonable research into applying cathodic protection to metal structures such as pipelines, research for reinforced concrete structures is very limited. This paper combines academic research with industry standards and guidelines in order to present the topic succinctly while covering all aspects. The review also delves into novel and renewable cathodic protection systems and highlights areas that are still unknown with regard to requirements for impressed current and the protection levels achieved.

I look forward to your response.

Sincerely,

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1. Byrne A, Byrne G, Davies A, Robinson AJ. Transient and quasi-steady thermal behaviour of a building envelope due to retrofitted cavity wall and ceiling insulation. Energy and Buildings. 2013 6//;61(0):356-65.

HIGHLIGHTS

Click here to view linked References

- Cathodic protection systems for reinforced concrete structures
- Comparison of sacrificial anode and impressed current systems
- Details of anode systems and their specification
- Power provision for impressed current CP
- Advances in renewable and novel power provision for CP

Cathodic Protection for Reinforced Concrete Structures: present practice and moves toward using renewable energy

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Abstract

Cathodic protection (CP) limits the corrosion of a metal by making it the cathode of an electrochemical cell. This is achieved either by (i) using more active sacrificial anodes to create a driving current, or (ii) using inert anodes and impressing an external direct current (DC). This paper presents up-to-date CP systems available for reinforced concrete, particularly Impressed Current Cathodic Protection (ICCP) and self-sufficient or renewable energy systems. The potential for overcoming the mismatch in energy provision from renewable sources (intermittent current) with energy needs for CP (constant current) is discussed by exploring novel designs and examining current requirements.

Keywords

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1 Introduction

Major corrosion damages on reinforced concrete buildings were first documented in the 1960s, with reports increasing considerably since 1975. Corrosion has become a major issue in maintaining infrastructure[1]. Corrosion of metal reinforcement leads to damage, deterioration and destruction in concrete structures. Excessive corrosion can lead to dangerous unanticipated failures and costly repairs[2-4]. The annual cost of corrosion worldwide is estimated to be 3% to 4% of the Gross Domestic Product (GDP) of industrialised countries[5, 6]. In the US, the American Society for Civil Engineers (ASCE) reported that a $17 billion annual maintenance investment was needed to substantially improve bridge conditions[7]. In Western Europe, the annual cost of repair of reinforced concrete structures is in excess of €5 billion[8]. Corrosion can proceed more rapidly in structures exposed to chloride environments, these include coastal structures exposed to seawater and roads where there is frequent use of de-icing salts. In Ireland, the current road network contains approximately 1,500 concrete bridges, 330 of which are within two miles of the coast and are therefore more susceptible to chloride ingress and corrosion[9].

Corrosion of embedded steel reinforcement is an oxidation reaction. As shown in Figure 1, the area of corrosion becomes the anode in an electrochemical cell. A harmless reduction reaction occurs at the non-corroding, cathodic, points in the reinforcement. Electrical current flows towards the anode (the opposite direction to electron flow by convention) along the steel.

Methods of limiting or fixing the effects of corrosion include patch repair [10, 11], surface treatments [12, 13], electrochemical chloride migration [14, 15], re-alkalisation (for carbonated structures) [16, 17], chemical impregnation with corrosion inhibitors [18-20] and cathodic protection (CP) [21-23]. Interconnected influences to consider when designating repair techniques include weight restrictions, budget, the need for a monitoring system, maintenance requirements, traffic management during repairs, the extent and severity of damage, aesthetics and technical limitations[24]. Patch repair is the most widely used option but it is limited to localised damage or where the impact of that damage is of little significance[24]. The disadvantage of this choice is the risk of incipient anodes causing corrosion of the surrounding areas of reinforcement[25]. Surface treatments are usually used as a preventative measure or in combination with other techniques. Coatings are physical barriers to prevent the ingress of chlorides and carbon dioxide. Both coatings and surface treatments are best suited to early chloride or carbon ingress, before the reinforcement is likely to have corroded. Impregnants are low viscosity liquids which line the pores in the concrete, preventing the migration of ions. Corrosion inhibitors reduce the rate of metal dissolution; it has not been established whether inhibitors can stop or significantly reduce the rate of corrosion and may only provide additional protection against initial corrosion, therefore they are only adequate in a small number of circumstances[24].

CP introduces an external anode and applies a small current onto the reinforcement, forcing it to act as the cathode (as opposed to the dissolving anode) in an electrochemical cell. It controls corrosion in the whole area being treated which reduces the extent of concrete repair-work necessary[25]. Chloride extraction is similar to cathodic protection but it involves a much higher current density and is a once-off application. The chloride ions are drawn out of the concrete and towards the anode and are extracted into an electrolyte in the anode. This process also increases protective hydroxyl ion concentration. This method is only effective in the cover zone of concrete removing 70% of chloride ions from this zone[24]. However, it is not recommended for use with pre-stressed wires as the increased risk of hydrogen embrittlement can cause the reinforcing wires to fail. There is also a risk of initiating alkali aggregate reaction due to the increased pH. Re-alkalisation is the alternative to chloride extraction for carbonated concrete and is also a once-off treatment. With this method there is less of a risk of alkali aggregate reaction, nonetheless, it can still occur in areas without carbonation issues. Again there are limitations with its use with pre-stressed structures

CP is particularly effective where chloride contamination is the cause of corrosion [26]. Current flows from the external anode to the reinforcement through the concrete forcing a beneficial cathodic reaction to occur at the steel surface creating hydroxyl ions. Hydroxide ion production increases the pH and its charge encourages the migration of chloride ions away from the reinforcement and towards the anode at the concrete surface[23].

For CP of reinforced concrete, research has either centred on the anode materials and type used[27-31], novel monitoring systems[32, 33], or examining current distribution within the reinforcement[30, 34]. Studies found that the majority of current is impressed on the reinforcement placed nearest the surface, with little protection afforded to the other layers[34, 35]. More severe corrosion rates show less even distribution of current[30, 34]. Concretes with higher electrical resistances result in less current distribution[30, 34], however, for a given current distribution, the high resistance of the surrounding concrete promotes passivation of the steel[34]. For anodic overlays, the proportion of the electrically conductive element, such as graphite, needs to be incorporated at an optimal level in order to enhance conductivity without compromising the required mechanical properties[28, 36, 37]. Reviews of cathodic protection systems for reinforced structures have been produced as technical reports for industry[22, 26, 38, 39]. However, many of these documents were produced in the 1990s [22, 38] when cathodic protection was in its infancy.

The most extensive research in cathodic protection focuses on metal pipelines[40-43]. Issues examined have included optimising the anode material and position[44-47], the degradation and disbondment of coatings[48-50] and understanding and mitigating other methods of failure [40, 51, 52]. There are a number of studies of the use of renewable energy sources for powering cathodic protection of buried or submerged metal structures[42, 53-57]. However, these have not examined the energy storage used to allow for the intermittency of such sources. In fact, disclosure of the mode of storage is often omitted entirely. As commercial enterprises reach to create new and more efficient stand-alone sustainable systems[58, 59], there is a need for research to underpin this progress.

This study is the first to summarise and tabulate findings from industry standards and guidelines, corporate experience and academic research on different methods of cathodic protection for reinforced concrete structures. Mindful of the accelerating shift towards using renewable energy systems, rooted in European Union (EU) and international directives[60], this paper discusses alternative energy sources for ICCP of reinforced concrete structures. The paper identifies research gaps in areas where greater understanding has the potential to create more efficient, sustainable, autarkic systems for the cathodic protection of reinforced concrete structures.

2 Cathodic protection technologies for reinforced concrete structures

Cathodic protection began for reinforced structures in the 1970s with applications in the USA for bridge decks where de-icing salts were common. This extended to buildings, tunnels, marine structures and substructures throughout the USA and Europe in the 1980s[26]. Existing damage to the concrete must be repaired before a CP system can be installed, though the extensiveness of repair is much less than what is required for repair-only cases[26]. The cracked or spalling areas of concrete are removed so the steel can be cleaned superficially before a cementitious mortar is applied. Highly resistant polymer mortars and bonding agents cannot be used in the case of CP as they would block the protection current. Overlays and repair mortars used in conjunction with CP systems should have similar electrical conductivity to the existing structure to allow ample current to flow. Surface preparation, usually by sand or water blasting of continuous reinforcement ensures all of the structure is protected. The continuity of reinforcement is determined using resistance measurements. Gaps in reinforcement are dealt with by cutting slots into the concrete and welding bars between reinforcement bars[26]. A minimum cover depth to the reinforcement is needed to limit short circuiting between the anode and cathodic steel.

CP provides external electrons to the reinforcement by introducing a new anode of a more active material than the steel. The reinforcement steel becomes the cathode and further aggressive corrosion is prevented[22] . Due to the high resistivity of concrete, galvanic anodes often cannot economically deliver enough current to provide protection. In these cases, more costly impressed current cathodic protection is used[29]. The basic galvanic or sacrificial anode cathodic protection (SACP) system is shown in Figure 2 and the impressed current cathodic protection (ICCP) system in Figure 7. Both systems have an anode, a continuous electrolyte between the anode to the element being protected and an external wire connection system. ICCP systems typically require a constant low direct current (DC) power supply to each independently controlled anodic zone[29]. This DC power source is normally from an electrical grid or generators for more remote locations, both of which are usually unsustainable sources of energy[38, 61]. There are few examples of research examining alternative DC sources for ICCP in concrete[38] and only one example of a renewable ICCP systems could be identified for a reinforced concrete structure [62].

There are several anode types used for both galvanic and impressed-current systems[25, 35, 39, 63]. Planar anodes (such as meshes and coatings) are the most effective configuration for reducing concrete resistance and improving current distribution to reinforcing bar[64]. However, other anode types can be preferable depending on design and operational requirements. Details of these designs are provided in relevant standards [25, 35, 39, 63], presented in Table 1, and summarised in the context of SACP or ICCP in sections 2.1 and 2.2 respectively.

2.1 SACP

SACP employs reactive metals as auxiliary anodes that are electrically connected directly to the steel to be protected. The difference in electro-chemical potentials between the anode and the steel causes a positive current to flow in the electrolyte, from the external anode to the reinforcement as per Figure 2. The whole surface of the reinforcement, therefore, becomes a more negatively charged cathode and the new anode corrodes sacrificially.

The experience of one engineering firm found that the sacrificial anode method is used more commonly in cases where small targeted repairs are required, where there is limited budget or where the structure has a shorter life expectancy [29]. This is due to the uncertain lifespan of the anode which is dependent on its average current output and the finite material available for sacrifice. The current provided cannot be controlled and changing conditions alter the required current drawn and therefore the amount of anode being consumed. New deterioration is the most likely first sign that the anode has been spent.

Compared to ICCP, galvanic systems have the advantage of being independent to external electric power and are less liable to cause interaction on adjacent structures [65]. Interaction is particularly prevalent in buried or immersed steel structures but also occurs for buried or submerged concrete structures. The flow of cathodic protection current from the CP anode through the water or soil can go through other structures nearby causing corrosion at the point where the current leaves the adjacent structure and returns to the protected structure [66]. Interaction can also occur within the same structure if there are metal items not attached to the reinforcement cage being protected.

Galvanic systems are the simpler of the two, requiring no continuous power supply or control systems. However, this means that the level of protection and current provided can be monitored but cannot be controlled. Thus changes in the structure, such as the deterioration of a coating, that can cause an increase in protection current demand, may necessitate the installation of further sacrificial anodes to maintain protection. Furthermore, the SACP anode lifespan tends to be shorter than ICCP, as the material is eaten-away. While a low driving voltage may be undesirable for most reinforced concrete structures, it is a safer choice for pre-stressed structures. As low resistivity is a requirement for effective galvanic protection [67], the main limitation of this type of cathodic protection for use with reinforcement is the relatively high resistance of the cover concrete. SACP systems provide a low current, limiting its effectiveness in high resistance environments. These systems are often used on oil platforms for both concrete and steel structures below water [67].

2.1.1 Anode selection

Anodes for SACP systems are made from less noble material than the steel being protected and are consumed preferentially to create the cathodic protection current [25]. Typical materials used are zinc, aluminium or magnesium. These metals are often alloyed to improve the long-term performance and dissolution characteristics, for example Aluminium-Zinc-Indium. Zinc and its alloys are the most commonly used for reinforcement in concrete structures [67]. The main drawback is "passivation" of zinc in this environment which creates an oxide layer on the surface that changes its potential. Therefore, zinc alloys may be used instead to reduce the formation of this layer. For reinforced structures sacrificial anodes can be a zinc mesh and overlay, or a zinc sheet attached to the concrete using a conductive gel or flame sprayed zinc [26]. Aluminium and magnesium and their alloys are used less regularly as their oxides and corrosion products can attack the concrete [67]. However, examples exist where they have been used successfully [27]. A summary of anodic materials and designs is displayed in Table 1 with further discussion presented in the following sections 2.1.2 to 2.2.7.

2.1.2 Metallic coating anode

Primary anodes of titanium, stainless steel or brass plates are fixed onto the concrete surface with an insulated epoxy. The zinc based coating is then sprayed onto the prepared concrete surface and connected directly to the steel [63]. The process of metallizing involves the melting of a metal or alloy in the form of wire, typically by a high amperage arc, and spraying the molten metal onto the concrete with compressed air as per Figure 3. This form of anode results in a grey or metallic surface finish which can be covered with a decorative silicon coating. It is often used in the splash zone in marine environments [63] and is not designed for wearing surfaces.

2.1.3 Anode jackets

Clamp-on and wrap-around systems are used in splash, and higher, zones, as well as concrete piles [63]. They consist of zinc anodes in activated mortar or a zinc mesh in prefabricated form grouted onto the concrete. They are typically fitted using a prefabricated fiberglass jacket which has the mesh anode attached to the inside of the jacket using special offsets. The jacket system is mounted to the piles using compression bands and the void between the jacket and concrete surface is filled with a cementitious grout [69]. An example of a jacket system is shown in Figure 4.

2.1.4 Adhesive zinc sheet anode

Adhesive anodes consist of rolls of high purity zinc foil which is coated on one side with low resistance ionic conductive hydrogel [63]. These anodes can be applied as rolls or sheets directly to the surface of the concrete using the gel adhesive [67]. Heavy moisture intrusion can degrade the gel so careful sealing at the edges is important [63]. An example of this system applied to a concrete balcony is shown in Figure 5.

2.1.5 Repair/discrete anodes

Embedded anodes for patch repair are not designed to provide full CP to the steel, but to further the protection provided by the repair process. Normally at corrosion points in reinforcement, the anodic action provides a natural protection to the adjacent steel similar to Figure 1 whereby the neighbouring steel is relatively cathodic. When the damaged area is repaired and patched up, the previously protected adjacent lengths of steel can begin to corrode as they are now more active than the repaired portion. Installers can embed sacrificial anodes into the patch repair in the hope of preventing such an issue [67], as per Figure 6. Simulations have shown that this type of sacrificial anode is able to arrest macro-cell corrosion that originates from patch repair [73].

Similar discrete style anode arrays can also be placed in drilled holes at intervals throughout a concrete structure for more even protection. These can be designed as stacks of zinc disks on a central zinc core, surrounded by lithium based mortar which activates the zinc [63]. Discrete anodes can be connected to the steel directly individually or as an array. The protective current provided by discrete zinc anode corresponds to the reinforcement corrosion current, increasing when there is higher risk of corrosion such as adverse weather conditions [75]. Under high heat and humidity discrete anodes may not provide adequate protection to the steel [76].

2.2 ICCP

Impressed current systems are the most commonly used for reinforced concrete [23, 25, 29, 30, 32, 33, 77, 78]. ICCP is used where electrolyte resistivity is high and galvanic anodes cannot economically deliver enough current to provide protection. These systems are conventionally used to protect atmospherically exposed concrete structures, particularly due to chloride ingress [67]. ICCP is used most commonly to address significant corrosion issues in larger structures with longer life expectancies, and where access is difficult [29]. These systems can control corrosion at any chloride level, and, due to its ability to alter the current provided, it can account for the changing protection requirement over time and between different anodic zones. They employ inert (zero or low dissolution) anodes and use an external source of DC power (usually converted from AC by a rectifier) to impress a current from an external anode onto the cathode surface. By forcing a direct current into the reinforcement cage it increases the cathodic reaction, which produces more hydroxyl ions from oxygen and water. These ions migrate through the concrete cover to the anode where they oxidise to produce oxygen and electrons. The electrons then flow through the anode cables and back to the current source.

The basic elements of an ICCP system and their functions are as follows [23] with reference to Figure 7:

- An external electrode (the anode) is mounted on the concrete surface.
- This electrode is connected to the positive terminal of a low voltage DC source.
- The negative terminal of the DC source is connected to the reinforcement cage to be protected.
- Through the reinforcement cage, electrons flow to the steel/concrete interface increasing the cathodic reaction (which produces hydroxide ions from oxygen and water).
- Hydroxide ions then migrate through the concrete cover to the anode.
- At the anode they are oxidised to oxygen and electrons.
- The electrons flow to the current source which closes the electric circuit.
- Due to this current circulation, cathodic reactions at the steel are favoured and anodic reactions supressed.

Impressed current installations are able to supply a relatively large current, providing high DC driving voltages which, unlike SACP, allow them to be used in most types of electrolytes. Also unlike SACP, Impressed current systems can provide a flexible current output that can accommodate changes in the structure being protected [65]. Generally, however, care must be taken in the design to minimise interaction on other structures and, if the structure is remotely located, an alternative power source to the electrical grid (solar panels, diesel generator, etc.) is required.

2.2.1 Current requirements

Due to the complexity of the chloride/moisture/pH influence on corrosion it is not possible to precisely predict the current or potential required. Examples of estimated voltage and current requirements for ICCP include 1-5A and 2-24V to each independently controlled anode zone [29] and 10mA and 2-10V per m^2 of surface area of concrete respectively [22]. The recommended design current density is $0.02A/m^2$ [26] which refers to the circumferential surface of the bars, not the cross-section [26]. Bridges usually contain over $1m^2$ of steel surface per m^2 of concrete surface and buildings containing $0.5\text{-}1m^2$ of steel per surface m^2 [26]. This translates to a typical design current provision of 20mA per m^2 of surface area of the structure being protected.

ISO 12696:2012[35] is a performance standard for the design of cathodic protection systems for steel in concrete under atmospherically exposed, buried or immersed conditions. It designates how the system should be adjusted to provide the correct current. The standard also provides an outline of cathodic protection components, installation procedures, operation and maintenance amongst other details. Though it should be noted that it is only an overview of requirements and each system should be designed on a case by case basis.

2.2.2 Anode design

A range of materials have been used as non-consumable anodes for impressed-current systems. The sort of properties required by these anodes include good electrical conduction, low rate of corrosion and tolerant of high current densities at their surfaces without forming resistive oxide layers[79]. Examples of anodes used for ICCP include magnetite, carbonaceous materials (graphite), high silicon iron, lead/lead oxide, lead alloys and platinised materials such as titanium[79] which can provide relatively large protection currents without compromising durability[26]. Often a primary and secondary anode structure is employed. The anode that receives power from the external source is called the primary anode and it needs to have very low electrical resistivity[71]. The secondary anode receives the current from the primary anode, distributing it over the full surface of the concrete[71].

Concrete is highly resistant so the current cannot be distributed over long distances within it[38]. In submerged structures the anode may be placed away from the concrete as shown in Figure 8. However, for air exposed structures, the anode must be in direct contact with the concrete[39]. A distance of 0.2m from the anode is determined to be the maximum effective limit of current spread in the design of the anodic system[26]. Therefore, most systems are designed to cover the entire surface of the concrete where protection is required (coatings or overlays). Broomfield[22] states that the high resistance of concrete over the steel reinforcement makes it necessary to have anode distribution across the surface of the structure as opposed to just submerged in the water or ground nearby as is the case for pipelines or ships. Table 1 summarises anodic materials and designs.

2.2.3 Activated Titanium mesh anode

The most common and reliable ICCP anode is the activated titanium expanded mesh with a surface coating of mixed metal oxides and covered with a cementitious overlay[26]. The mixed metal oxide coating acts as the anode while the titanium provides a stable base material[71]. Titanium conductors are spot welded at regular intervals to facilitate the connection to the current source[80]. Figure 9 shows the fitting of the mesh to the concrete surface using non-metallic fasteners (a) and being spray-covered with mortar (b). Although titanium mesh/overlay systems are costly and heavy, they are robust with a life expectancy of over 25 years[26]. This type has a high tolerance for external moisture so surface preparation is very important to ensure good connectivity.

2.2.4 Activated Titanium wire/strip/rod anode

Activated titanium wires or strips, or titanium oxide rods, are placed in holes or slots which are then backfilled with a cementitious grout[26]. Light, robust titanium strips are used commonly and have expected lifespans of over 25 years[26]. Compared with overlay and coatings, this type makes little difference to the surface appearance of the structure. However, as the anode is inserted into the structure as opposed to being spread across the surface, there is a higher risk of short-circuits to the reinforcement. Figure 10 shows the schematic of rod (a) and ribbon (b) anodes with Figure 11 showing the installation of titanium mesh ribbon anode on site. Ribbon mesh anodes are extensively used in cathodic prevention whereby they are fixed to the reinforcement using plastic clips that maintain a distance between the anode and steel[80].

2.2.5 Organic anode coatings

Organic anode coatings are electronically active due to the high proportion of carbon particles[26]. A series of metallic conductors are embedded in the coating, as per Figure 12, as primary anodes to feed the current. The electrochemical properties of coatings depend on the carbon content. Coatings containing 45–50% graphite have been shown to have low resistances and potential stability at high polarisation levels[36]. However, such levels of graphite increase the porosity of the anode[37].

These systems are light, have a long history of use and are robust with a life expectancy of 10-15 years[26]. Unlike rod and mesh types, they have a lower tolerance to external moisture and may change the surface appearance of the structure.

2.2.6 Conductive cementitious anode

This form of anode consists of a primary anode such as woven mats that are embedded in a polymer modified cementitious overlay[26] fitted in a similar way to titanium mesh/overlay systems. The addition of carbon fibres to the cement mix enhances the strength, toughness and electrical performance[28]. Carbon fibre combines the advantages of titanium mesh and conductive coatings, resulting in a durable system that can still be applied in thin layers, adding little additional weight[26] with additives such as pumice aggregate capable of further reducing the weight[81]. There is little experience with this type of anode. One, possibly minor, disadvantage is it changes the surface colour of the structure. The electrochemical property for higher fibre content is more inclined to deteriorate in the presence of chloride ions[28], therefore, the design proportions of the mix needs to be carefully considered to provide the enough protection without compromising the integrity of the overlay.

2.2.7 Hybrid SACP/ICCP systems

In hybrid systems, a temporary impressed current is used in conjunction with a low maintenance galvanic system to restore and maintain alkalinity. This form is used mainly with discrete sacrificial anodes connected to titanium wires for impressing the current for a short period after instalment[63].

2.3 Comparison among cathodic protection methods

Overall the benefits of using cathodic protection for reinforced structures above other methods includes less concrete removal and repair work, a wide variety of choice in anode type and low monitoring and inspection time and costs[25]. However, care must be taken to avoid hydrogen embrittlement in the steel, alkali silica reaction in aggregates and interactions with adjacent structures[25]. Table 2 compares SACP to ICCP for reinforced concrete structures.

3 Power supply and control systems for ICCP

Normally for ICCP the power supply is via a "transformer rectifier" system [22]. The transformer reduces the mains voltage from 240V or 110V to under 24V per anodic zone as discussed in section 2.2.1. The rectifier circuit converts alternating current (AC) to direct current (DC) as is the requirement for cathodic protection. Since the precise current required cannot be predicted, a safe value of $0.02A/m^2$ of steel surface is often used to design the power unit initially [26]. Conservatively this can include all the steel in the structure, but usually only the steel nearest to the surface is taken into account.

There are many companies providing products, prescribed solutions and installation and maintenance of cathodic protection systems [82-85]. A full state-of-the-art kit for ICCP consists of anodes, power supply, junction boxes, test stations, remote monitors, cable and splicing, reference electrodes, over voltage protection, isolators, inspection equipment and surface preparation equipment [82].

3.1 Monitoring systems

Maintenance involves fault finding, repairs to surface anodes and replacement and fixing of parts [25]. A study of over 100 CP installations found that the average time until minor repairs of parts is about 15 years and that the need for complete replacement of the anode was rare [86].

Performance monitoring is prescribed at 3 monthly intervals for the first year then every 6 or 12 months afterwards if the performance has been satisfactory [25]. Performance monitoring comprises measurement of "instant off" free polarised potentials, measurement of potential decay over 24hrs or so, measurement of any other sensors installed, visual inspection, data assessment and adjustment of the current level if needed [25].

The quality of CP provided can be checked by measuring the amount of polarisation taking place in the structure. The shift in potential due to the impressed current indicates the level of protection provided [87]. A minimal provided polarisation reduces corrosion to insignificant levels. To determine this, a depolarisation test is carried out. The protective current is switched off and approximately 1 sec later (to allow for switching surge) the "instantaneous off" value of polarisation potential is measured. The structure is then left unprotected and allowed to de-polarise over the next 4 to 24 hours [26]. Standards recommend a minimum difference between polarised and non-polarised potential of 100mV as sufficient for atmospherically exposed concrete structures [26, 87]. If the potential is found to be too low, the ICCP voltage can be increased before the next test. The reinforcement is termed "overprotected" if the polarisation is too high. This can lead to reducing the life of the anode and reduced contact between the anode and concrete encouraging hydrogen evolution which is dangerous in pre-stressed structures [26].

Monitoring by depolarisation is based on the use of sensors at representative points in the structure called reference electrodes as shown in Figure 7. Half-cell reference electrodes, usually silver-silver chloride, are embedded in the concrete to monitor the potential of the reinforcement [71]. The potential of the steel at the concrete interface is measured with respect to these electrodes [39]. They are placed in the concrete, near the steel, in the most actively corroding zones before energising the system, with additional electrodes placed in areas of high reinforcement complexity [25]. Portable reference electrode mechanisms can be used directly on the concrete surface or in conjunction with less accurate Lugging probes [25]. Further requirements for measuring, monitoring and recording devices are specified in the standard ISO 12696:2012[35]. British standards and The Concrete Society Technical reports detail the design and placement of reference electrodes and monitoring in more detail [35, 39].

Impressed current systems require regular maintenance and monitoring [25, 35]. However, one American-based survey found that the majority of installed ICCP systems are not regularly monitored or maintained as the process was considered to be too burdensome [71]. Most modern systems are remotely monitored and controlled using telephone lines, mobile phone networks or internet connections [71]. There are also proprietary control and monitoring systems available which automatically execute depolarisation tests at set monthly intervals, storing the results [80].

4 Research advances in alternative energy systems for ICCP

4.1 Cathodic prevention

Cathodic prevention is similar to cathodic protection except that the external current is applied *before* any sign of corrosion has occurred, during construction or just after, as a preventative measure. This is often used where early depassivation of the steel reinforcement is likely, such as in marine environments. As the reinforcement has not begun to corrode the required current density is lower with examples of 0.002-0.005A/m^2 [66] or 0.0002-0.002A/m^2 [35] being estimated. As with cathodic protection, a 100mV is the recommended decay criterion to prevent corrosion [88]. The installation costs are also lower as the concrete does not need any surface preparation, drilling or finishing [25].

4.2 Intermittent or low current CP

If the only impact of CP is assumed to be the cathodic polarisation of the reinforcement, then in order to provide adequate protection, the applied current density must be greater than the corrosion rate current [89]. However, Glass et al. [78] demonstrated that a protection current of 60A/m^2 induced the passivation of steel even though the initial corrosion rate was considerably higher at 600A/m^2. This indicates that protection may be achieved with a current that is small compared to the corrosion rate, in Glass et al.'s case this was one tenth the size. The protective effects were mainly attributed to the environment at the cathode including the removal of chloride and oxygen as well as the production of hydroxyl ions and other intermediates which result from the cathodic reaction [90]. Studies into the effects of CP on the concrete environment have shown that after a CP system is turned on the cathodic area initially becomes very alkaline and the anodic area becomes acidic, with the acidic area then spreading out from the anodic electrode towards the cathodic area[91]. It was found that the alkalinity is produced at the cathodically impressed rebar as the impressed current uses up the dissolved oxygen, requires the hydroxyl ions to carry the ionic current and produces hydrogen [91]. Furthermore, where chloride ingress is the cause of corrosion, cathodic protection draws these aggressive ions away from the steel due to the flow of negative ionic current away from the metal surface [90]. This environment encourages the growth of the protective passive layer on the steel, thus reducing the required protective current. More recent microscopic examinations have revealed that in areas of reinforcement without a protective layer, CP can keep the chloride ions 100 µm away from the steel surface, thus efficiently protecting the steel reinforcement [92].

In Glass et al.'s work [78, 89, 90] the changes in the environment of the steel that encourages the creation of the passive layer in concrete continues after current interruption. Intermittent current tests observed comparable results to constant current tests. Similarly Christodoulou et al. [77] found that for in situ cases of ICCP on reinforced structures, when CP was removed after five or more years of protective current, the steel remained passive for another year even with the continuing presence of chloride. Kessler et al. [93] evaluated an intermittent ICCP technique using photovoltaic energy on bridge concrete piles. It was found that after CP is removed and depolarisation naturally occurs, the polarisation level can still remain within established CP criteria as long as the initial applied current was sufficiently high.

4.3 Use of renewable Energy

If access to the main electricity grid is difficult, a diesel generator (connected to a rectifier) or some form of renewable energy system can be prescribed [35, 39]. Grid-based and generator power tends to use high fossil fuel consuming sources, with 82% of the world energy demand created by the burning of fossil fuels in 2011[61]. For concrete structures in remote or difficult-to-access locations, power can be supplied by self-sufficient renewable systems such as thermo-electric generators, closed-cycle vapour turbines, wind or solar energy [65].

Both wind and solar systems require batteries, or other energy storage mechanisms, due to the intermittency of their supply. Solar-powered systems can be used to provide current to the ICCP system during the day and to recharge storage batteries to provide current by night or during times of cloud cover [54]. Wind power can be suggested as the more viable solution than photovoltaics (PV) in certain remote locations or where regular cleaning of the solar panels is both required and difficult[94]. Originally remote ICCP systems were heavily wind power based [95]. PV modules have since surpassed them in usage with few examples of other renewable energy sources still present in industry [95]. Research reflects this trend, focusing on PV power above other renewables for CP.

4.3.1 PV systems (for metal pipelines)

Within academic literature there are limited examples which focus on renewable energy as a source for ICCP. Where examples do exist, they tend to be for buried pipelines [42, 96]. Solar energy systems are undeniably the most researched [42, 54-57, 96, 97] and industrially produced [58, 59, 98] renewable energy source used for cathodic protection.

An example of a commercially produced PV powered ICCP system is shown in Figure 13. The basic design of a PV cathodic protection system involves [54, 56];

1. PV modules. These are arrays of solar cells.

2. A charge controller to prevent the batteries from overcharging. The input port connected to the PV array and the output connected to the storage batteries. It provides a suitable charging current according to the battery state of charge, which protects them from overcharging.
3. Battery or array of batteries. These are designed to store PV energy, with enough to provide the required power for two days being considered adequate [56].
4. The electronic control unit is energised by the storage batteries and acts as a voltage regulator for the load (Load voltage regulator (LVR)). This part of the system can consist of maximum power point tracking (MPPT).
5. Auxiliary components of anodes, or reference electrodes, indicating the state of corrosion

Research within the area of PV for cathodic protection focuses on two separate steps in the system, (i) the management of power going into the battery or batteries, and (ii) the supply of the power from the battery or batteries to the structure being protected. Figure 14 displays these separate steps and presents the basic design of a PV – battery – cathodic protection system for buried pipelines as derived from different designs [54, 55, 57].

In standard practice guidelines [35] the current supplied to the steel is held at a constant value. Resistance of mediums such as soil can vary greatly with climatic conditions. If the applied DC voltage is held at a constant level, the impressed current on the metal being protected will fluctuate due to the varying resistance of the medium according to Ohm's law (*Current = Voltage/Resistance)*. In these circumstances either over-protection or under-protection can occur. Manual adjustment can change the supplied voltage to accommodate the different resistances. There have also been efforts to automatically adjust the DC provided based on the changing requirement [55]. There are many papers which present different designed control circuits intended to regulate ICCP powered by solar energy for optimum protection and efficiency of the impressed current [54-57, 100]. One method of doing this is by monitoring the voltage between the buried pipe and the reference electrode. If they are outside the determined allowable limits then the DC voltage supplied is adjusted to return them within the limits [100]. The alternative to this is to measure the DC current and ensure it is kept within the limits by adjusting the voltage of the supply [100].

On the PV-to-battery end, modules can have relatively low power conversion efficiencies but the cost of the system can be reduced by using high efficiency power conditioners designed to elicit the optimal power from the PV cells [57]. By sampling the PV output, the system applies a selected resistance to get the most suitable output for its needs. Maximum Power Point Tracking (MPPT) [57] calculates the voltage at which the module is able to produce optimum power regardless of present battery voltage. The charge controller compares the output of the panels to the battery voltage and determines the highest power that can be put out to charge the battery. Without MPPT systems, a conventional controller connects the PV modules directly to the battery, forcing the modules to operate at battery voltage. This is not the ideal operating voltage required to produce the maximum power output from the modules. Using this power value, it determines the best voltage to get maximum *current* into the battery.

4.3.2 Gaps in the current research into PV cathodic protection

Research into renewable energy systems for CP has been predominantly for metallic buried pipelines. Occasionally this extends to other metallic buried structures such as metallic foundations on transmission towers [97]. Buried pipelines are the most common application for ICCP, therefore, more research and development has been focused in this area. Secondly, the influence of moisture content on concrete's electrical resistance is not as great as that for soil which rapidly changes at 15% moisture content [101, 102]. Thirdly, PV cathodic protection systems commercially are constructed similarly to Figure 13, at set intervals, along remote pipeline routes [103]. Conversely, most concrete structures requiring protection exist along route ways where there is ready access to utility mains power supply. If generators are used, there are easy access routes for maintenance and refuelling.

Error! Reference source not found. highlights the two areas of research in ICCP renewable systems which fit either side of the battery or energy storage system. Examinations have been made of PV to battery input efficiencies [42, 57, 96] and battery output to CP control efficiencies [56, 57, 100]. The battery, within the context of PV cathodic protection systems has had little focus even though a battery-only system may provide adequate protection [104] as discussed in the next section.

4.4 Battery-only systems

Kessler et al. [104] examined the use of galvanic batteries under laboratory conditions and on three bridges. These were purpose- designed zinc anode, aerated cathode in gel electrolyte batteries. The bridges used titanium mesh pile jacket systems or conductive rubber anode systems. They were tested in different combinations with or without an ohm voltage regulating device to control output current. The installed batteries functioned properly for about two and a half years on their own providing adequate protection. By using battery-only systems, the higher cost of PV-battery systems which require additional control and wiring mechanisms is eliminated. Higher current requirements can be accommodated by combining batteries.

5 Discussion

5.1 Filling the research gaps

More research is required for renewable ICCP systems for the protection of *reinforced concrete* structures. There is a need in all sectors to move away from fossil fuels driven by national and international plans and agreements to reduce EU energy consumption by 20% and increase renewables by 20% by 2020, compared to 1990 levels [60, 105].

The design of autonomous systems for ICCP could potentially be greatly simplified and the power required greatly reduced with more understanding of the level of protected needed and how intermittent it can be. A greater knowledge of this could result in renewable-only systems (without backup batteries), or battery-only systems providing adequate protection. Therefore, the three areas which present the most potential for progress include PV for reinforced concrete structures, novel battery systems for cathodic protection and further examinations into the intermittency and level of current supply needed to give adequate protection.

5.2 Intermittency: is energy storage necessary for PV CP?

Types of batteries currently in use in proprietary PV cathodic protection systems include, gel-batteries [59], lead-acid batteries [58], NiCad battery [58] and sulphuric acid based batteries [106]. These batteries are usually 12 V at 100-150Ah. Academic controlled test facilities and simulations also employ off-the-shelf battery solutions. Ghitani et al. [56] uses battery of type Delco S2000 of rating 100 Ah at 12 V for a 1m sample of steel pipe in soil powered by two solar cells each with a maximum output of 3.02A and 16.9V. Deep cycle batteries such as this are typically used with renewable energy systems. El-Samahy et al. [100] does not indicate the type of battery used in their PV-CP project but uses a battery bank of total 150 Ah at 12 V taking power from six solar cells of 2 V, 150 Ah each.

The main issue with liquid electrolyte batteries is the use of toxic materials and their tendency to leak during use or after disposal. Solid electrolyte batteries tend to provide inadequate power at room temperature and are more costly. Research into novel forms of battery focus on creating higher power storage, greater recharge capacity and extending their life by adapting components and materials. There has been very limited research into battery innovation for low energy requirements such as ICCP.

One piece of research demonstrated that PV could provide sufficient power for continuous cathodic protection without the need for a storage device. This was achieved by pre-polarising the protected structure to a high negative potential using a temporary DC source before energising for CP [53]. The slow rate of decay of the pre-polarisation facilitated continuous protection to the structure even during night time periods when there was no PV current supplied. Another example exists whereby sacrificial anodes were used as the backup energy source for when PV energy was down or low and no method of energy storage was employed [107].

Furthermore, recent research questions the necessity of continuous DC supply to achieve adequate protection particularly for reinforced concrete structures and chloride induced corrosion [77, 78]. This questions the necessity of having batteries or other energy storage facilities under certain circumstances. There have been limited, but reliable, examples of where intermittent current supply has provided adequate cathodic protection to structures [77, 78, 93]. Batteries, such as those designed by Kessler et al. [104], have been shown to provide constant low level energy over long periods of time. Secondly, the intermittency of renewable energy such as PV is well understood. If further research could demonstrate that intermittent current supply is always sufficient it could greatly simplify the design of such systems and lower the power requirement, which reduces resources, increases the amount of renewable energy usage in the sector and lowers power supply.

5.3 Summary and Conclusions

Corrosion is the major issue in reinforced concrete deterioration affecting serviceability and safety. A number or repair techniques have been developed, but these can be costly and disruptive with often unknown effectiveness. Cathodic protection has proven to be a reliable long-term solution for corroding concrete structures, particularly those subject to chloride ingress with techniques being refined continuously. This paper presented an overview of the main cathodic protection systems offered for reinforced concrete structures using up to date information from research and industry. The advantages and disadvantages of each form was presented and compared.

Impressed current cathodic protection has been used most commonly for reinforced structures as the high resistance of concrete requires higher and more controlled protection currents. Most research for reinforced structures focuses on the anode application method and material chosen. Activated titanium mesh anode systems are the most commonly used as they are the most reliable at delivering an even current to the entire surface of the structure and being very robust. This form does, however, add a relatively high additional weight. In structures where weight is an issue, probe or wire type anodes or sprayed coatings are preferred.

Impressed current systems rely on an external direct current power source. International targets for 2020 to reduce energy usage by 20%, increase the use of renewable sources of energy by 20% and reduce overall emissions by 20% of those recorded in the base year 1990 has put increasing pressure to achieve these goals[60]. This is evident in most sectors, including engineering and cathodic protection. However, the specific effort to make CP more renewable and environmentally friendly for reinforced concrete structures has not been observed. Without any articulated reason for this, it is suggested that perhaps historically there had been no necessity for it.

There are a number of examples of renewable energy systems for ICCP for buried metal pipelines which are relevant to reinforced concrete. Research tends to either focus on making the PV-to-battery step more efficient or the battery-to-CP step more efficient and effective. It was identified that within the context of making these systems more efficient, there was a lack of evidence of any such attempts focused on the power storage devices used. The possibility of using novel battery designs and other power provision and storage methods was presented, which could represent future low cost solutions for low-energy consuming systems such as cathodic protection.

This paper has presented the assumed requirement for constant DC power to provide adequate protection for reinforcement using examples in research where intermittent current was found to be sufficient. Standard guidelines based on site experience suggest a constant level of 0.02A/m^2 when designing ICCP systems for reinforcement. However, much lower values introduced intermittently have proved, in certain instances, to be adequate. There are two reasons identified for this.

i. The environment around the steel changes, even at very low current levels, to one that encourages the passivation of the steel and draws away destructive ions.
ii. After depolarisation, when the current source is removed, following the initial quick drop the steel will maintain a slight polarisation that may still be within allowable limits for protection according to standards.

This area requires further research. A greater understanding of the level and frequency of protection needed could facilitate the design of more efficient systems and the advancement in novel and renewable sources of energy for cathodic protection of reinforced concrete structures.

The number of assumptions and unknowns in cathodic protection for reinforced concrete are many. However, cathodic protection for such structures is presented as the most robust and reliable of the solutions for corrosion control. Cathodic protection probably will, and should, turn ever more towards renewable sources of energy. To make this more efficient, the power requirements should be more clearly understood and prescribed. The conclusion of this review analysis is that further research needs to be conducted into the potential for intermittent sources providing adequate protection, renewable energy based cathodic protection of *reinforced* structures, and the appropriateness of other novel power sources to ICCP.

Acknowledgements

The authors would like to express their thanks to Science Foundation Ireland (SFI) for funding this project through the Technology Innovation Development Award (TIDA).

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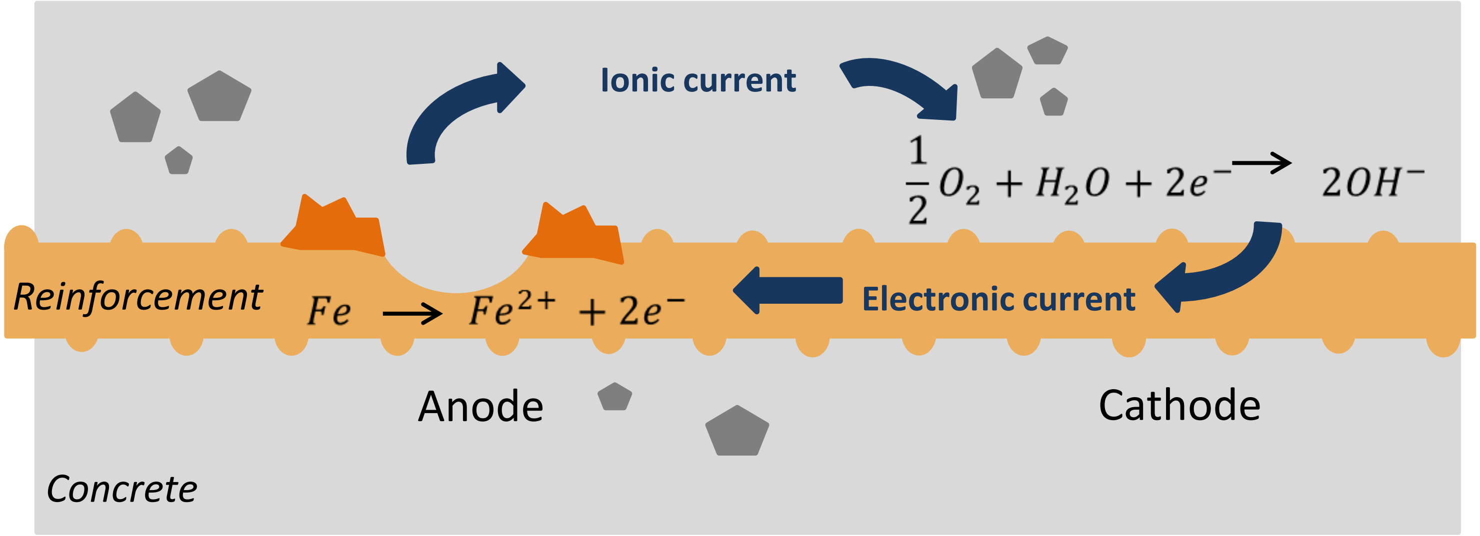

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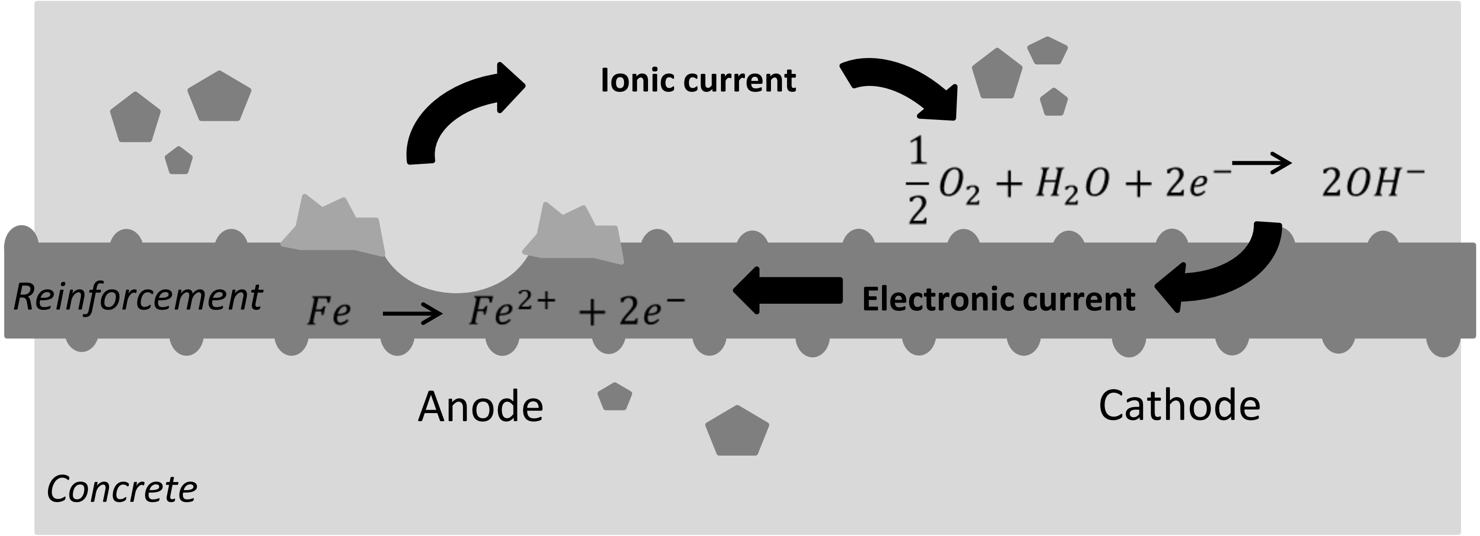

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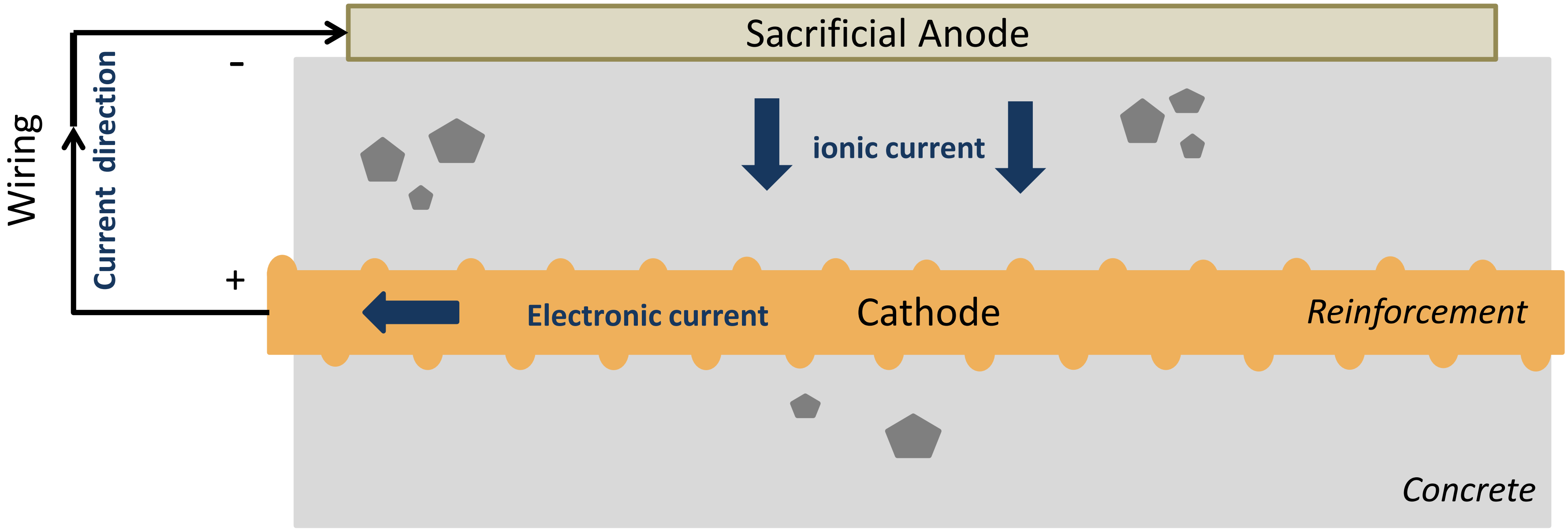

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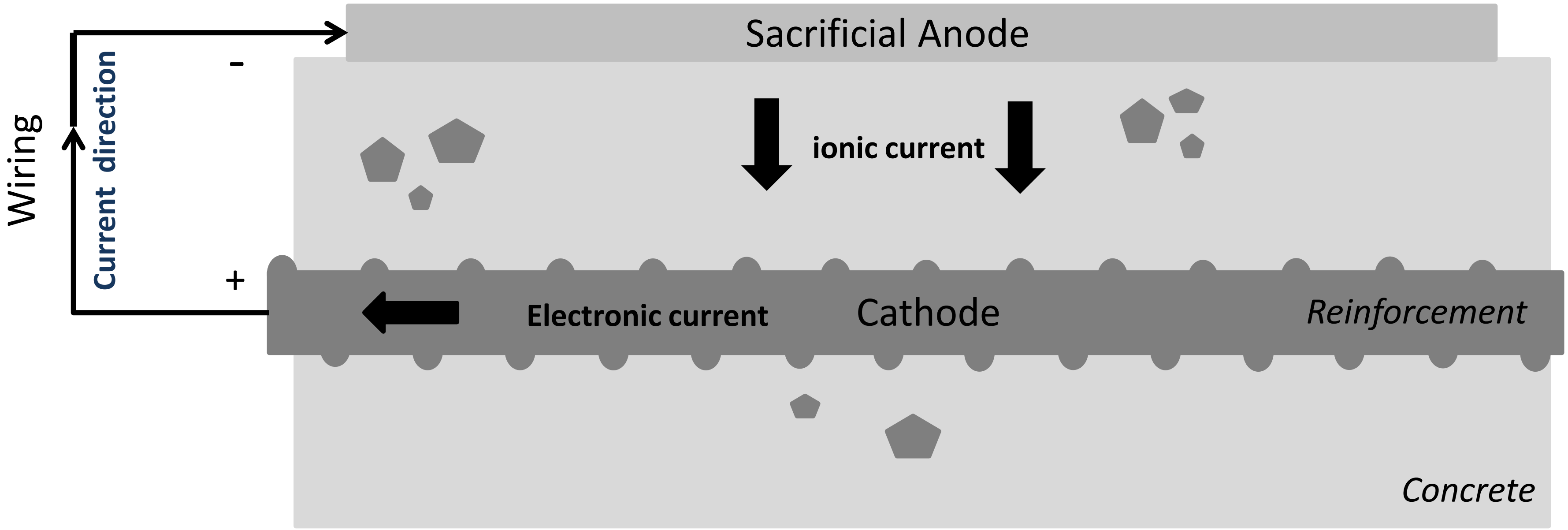


Figure 3 colour web

Figure 3 b&w print

Figure 4

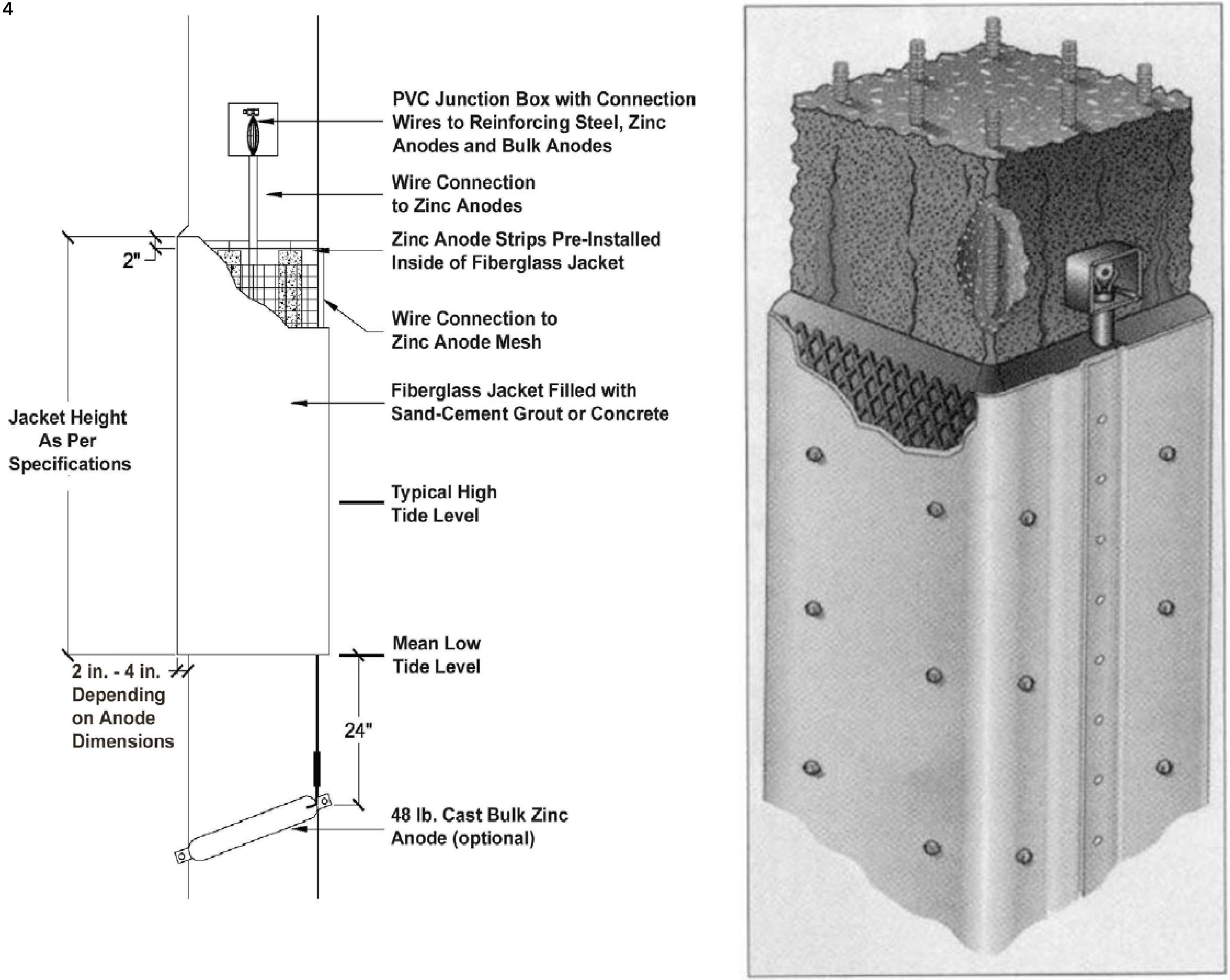

PVC Junction Box with Connection Wires to Reinforcing Steel, Zinc Anodes and Bulk Anodes
Wire Connection to Zinc Anodes
Zinc Anode Strips Pre-Installed Inside of Fiberglass Jacket
2"
Wire Connection to Zinc Anode Mesh
Fiberglass Jacket Filled with Sand-Cement Grout or Concrete
Jacket Height As Per Specifications
Typical High Tide Level
Mean Low Tide Level
2 in. - 4 in. Depending on Anode Dimensions
24"
48 lb. Cast Bulk Zinc Anode (optional)

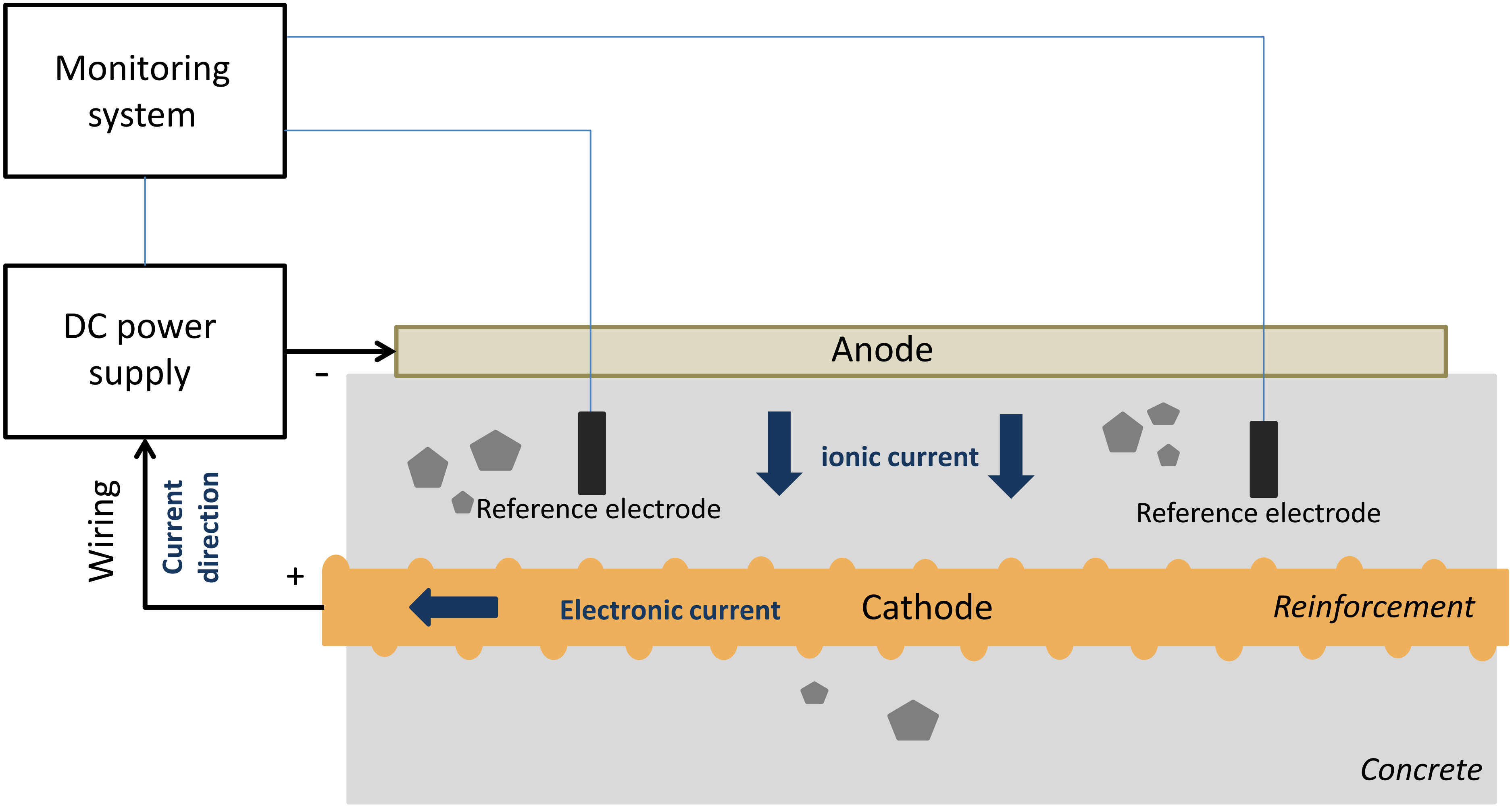
Figure 5 colour web

Figure 5 b&w print

Figure 6 colour web

Figure 6 b&w print

Figure 7 colour web



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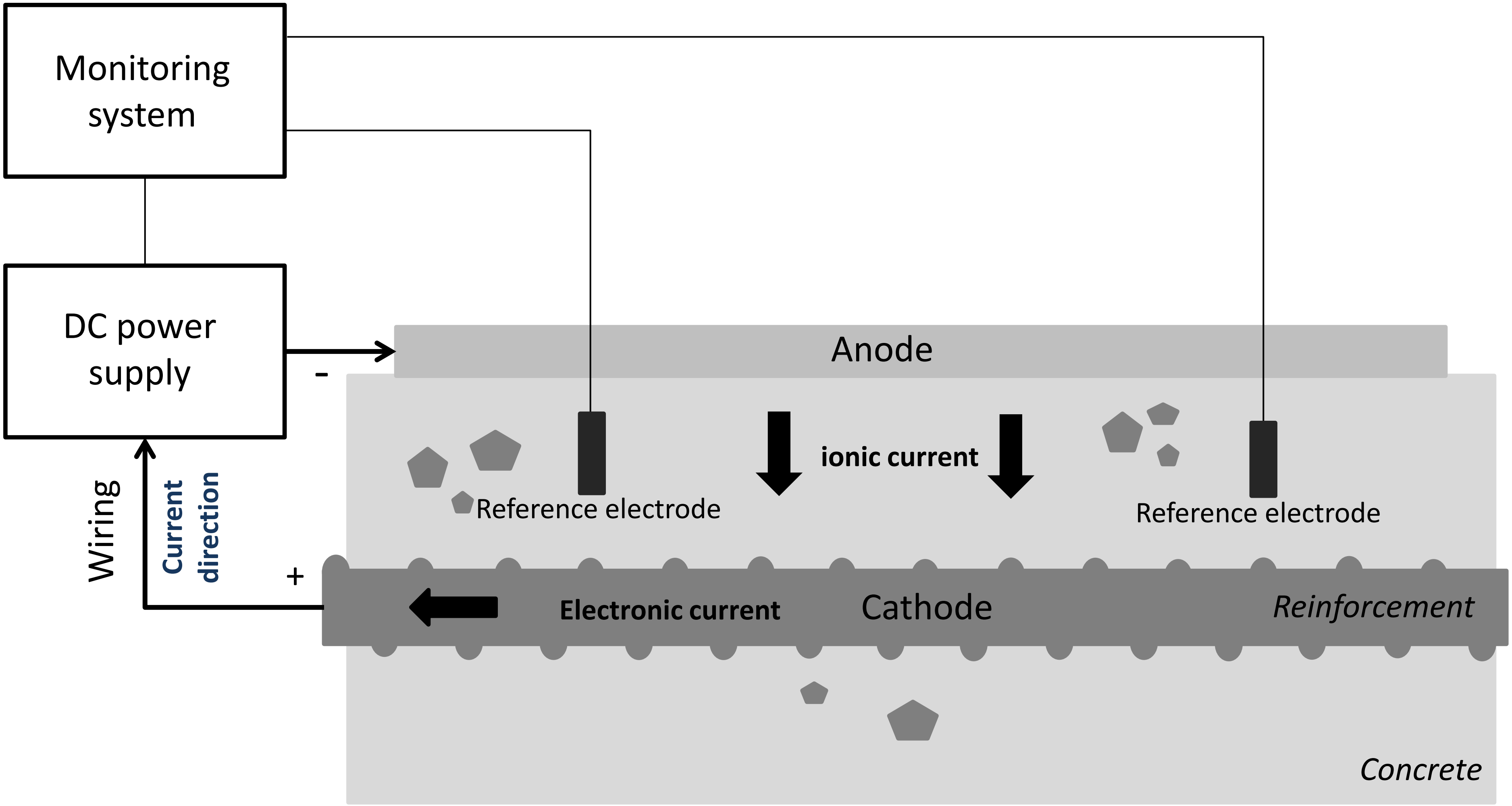

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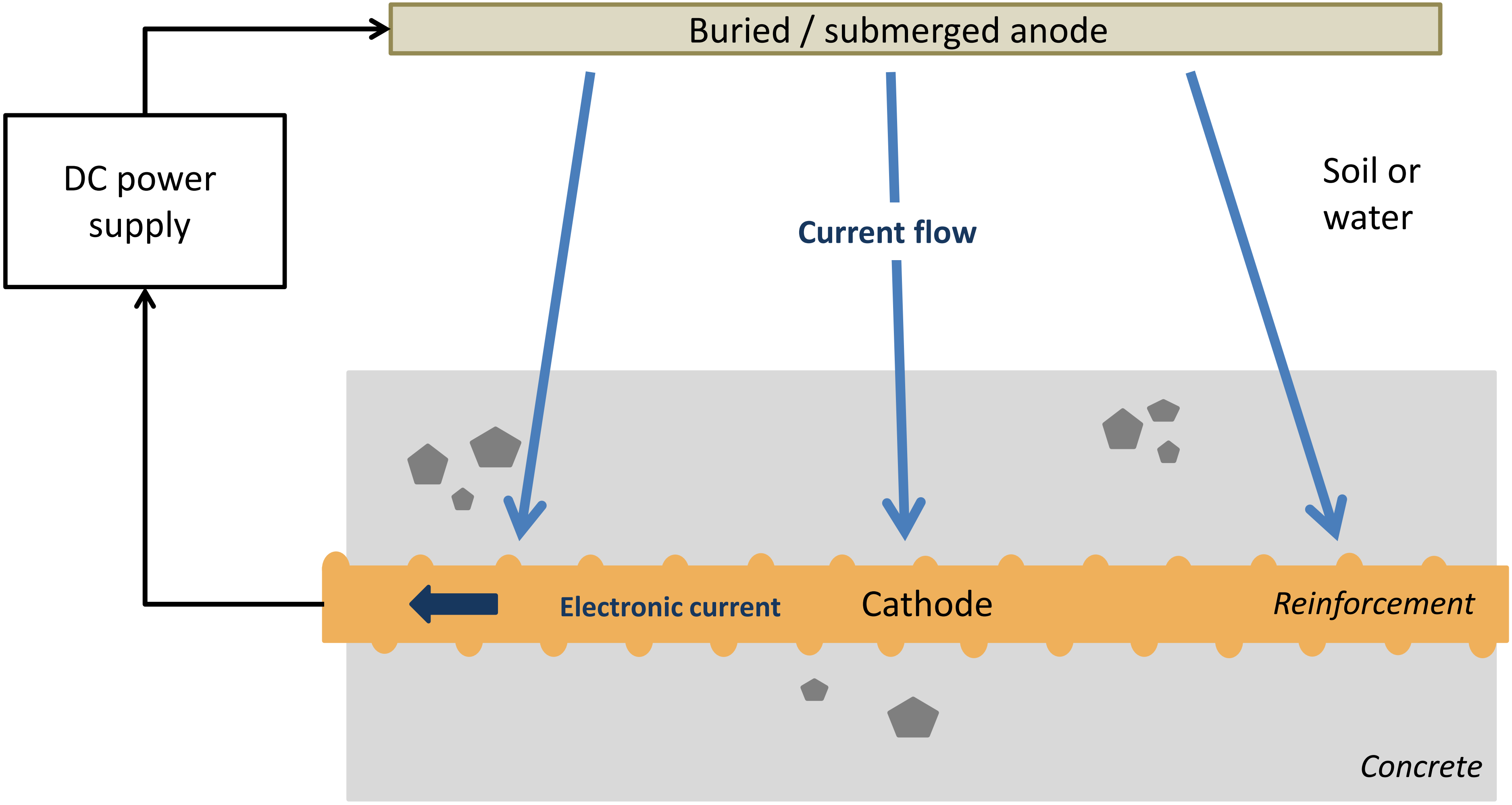

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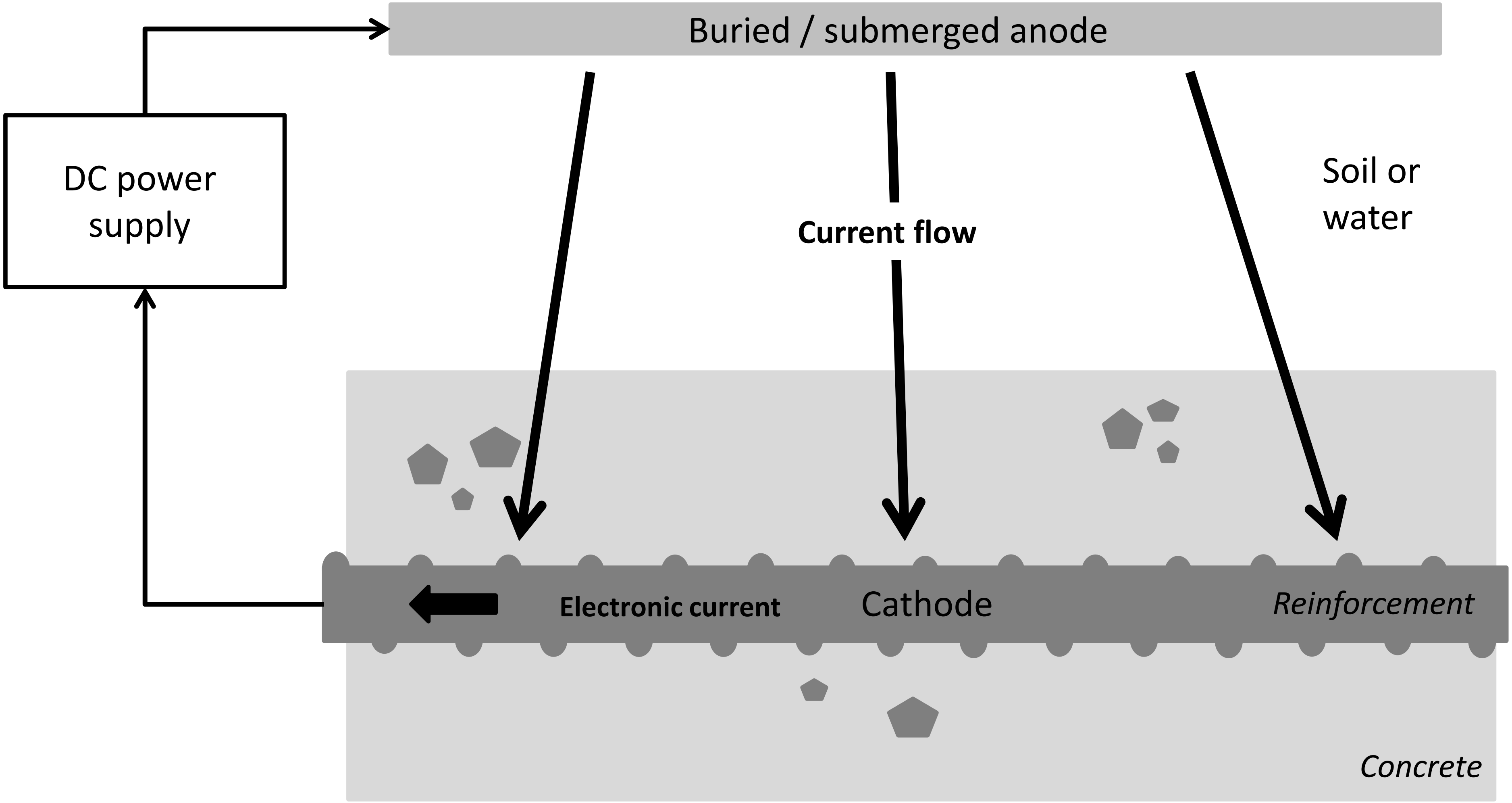


Figure 9 colour web

Figure 9 b&w print

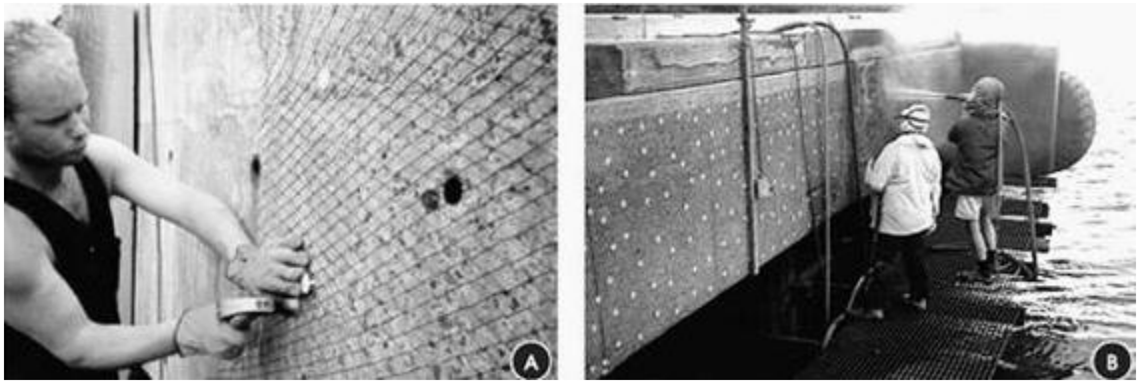
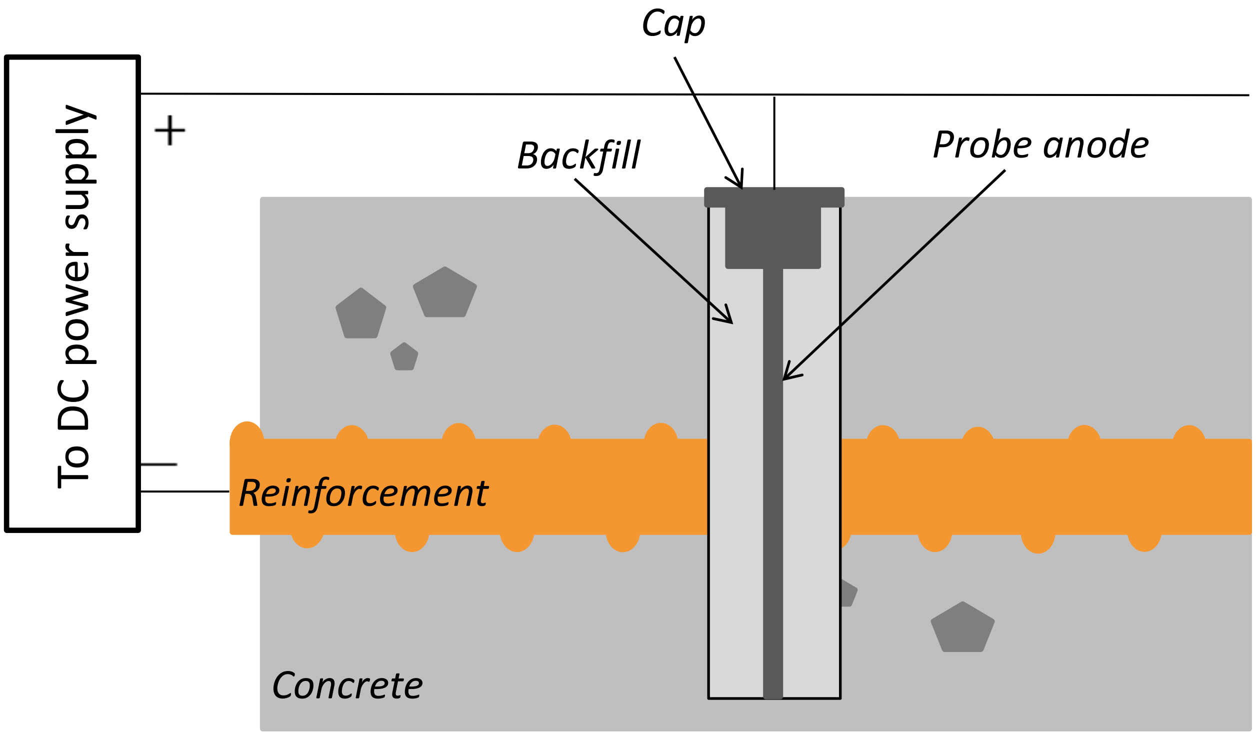


Figure 10 colour web



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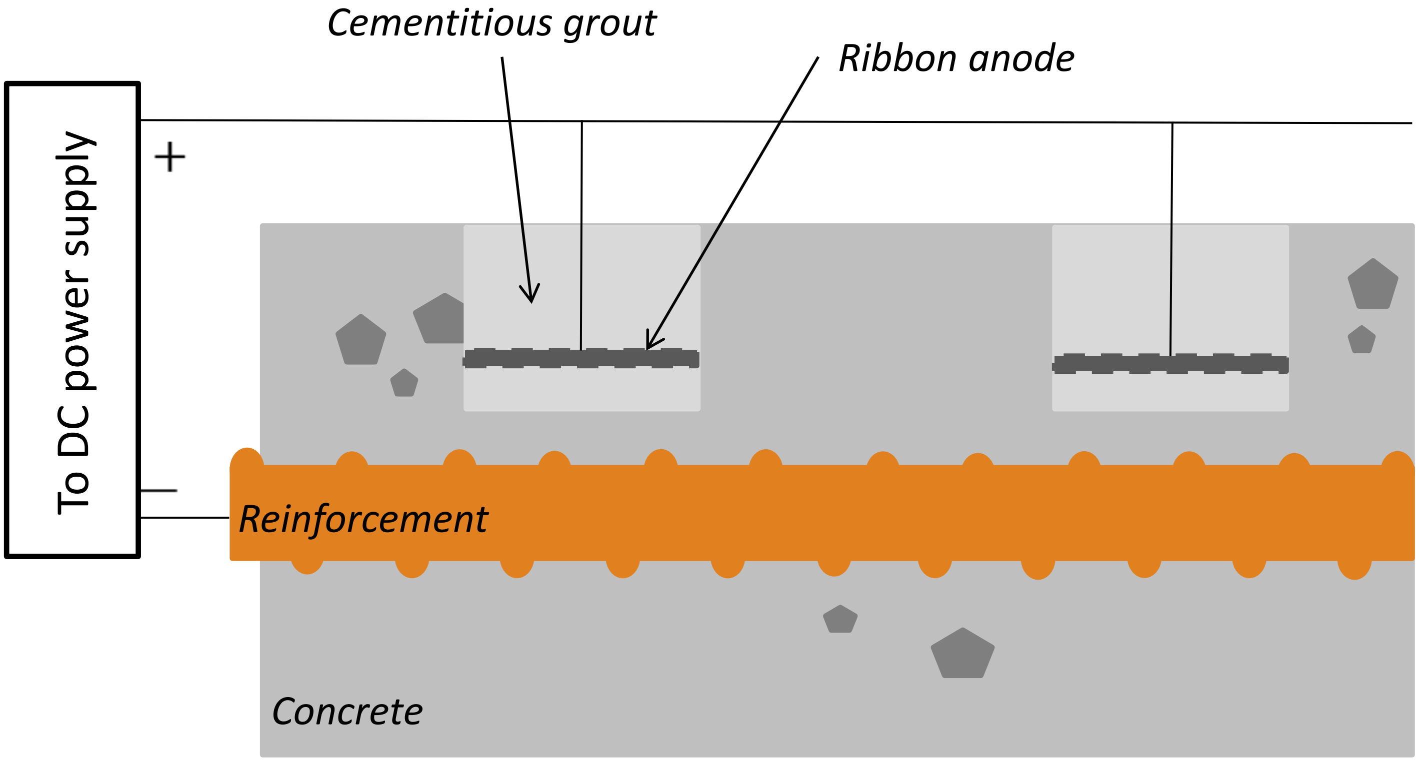
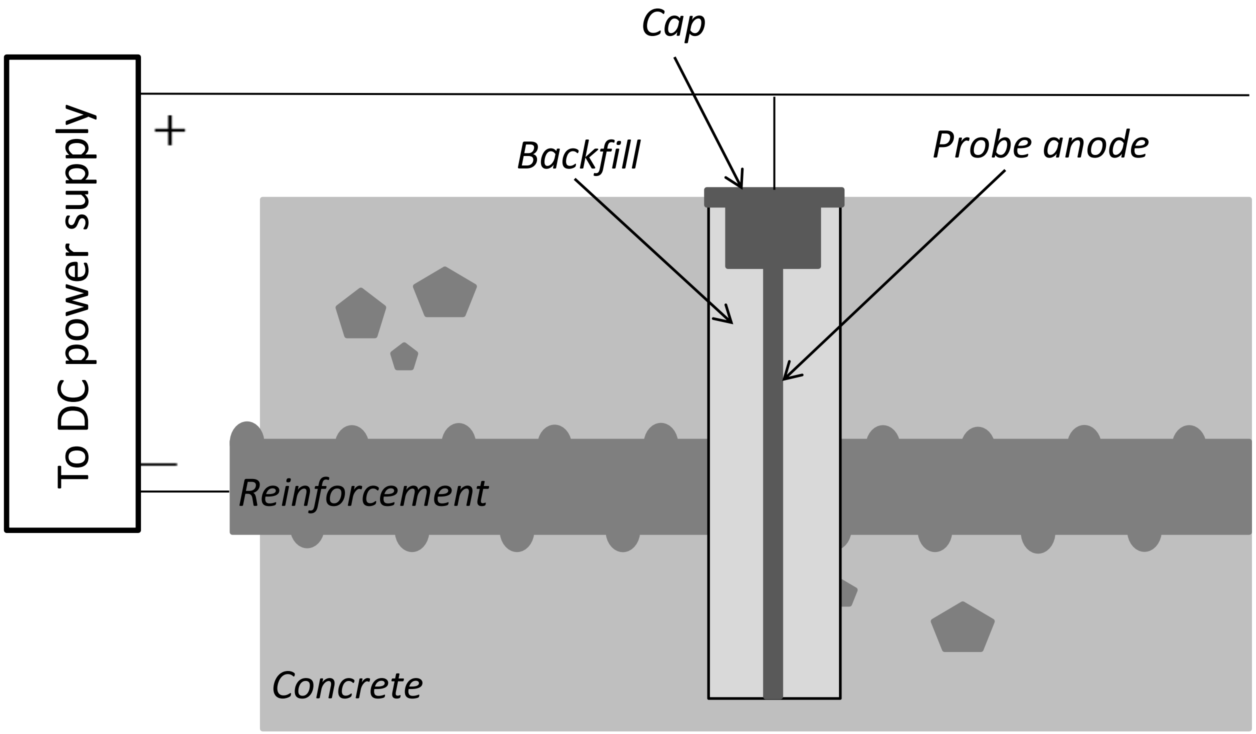
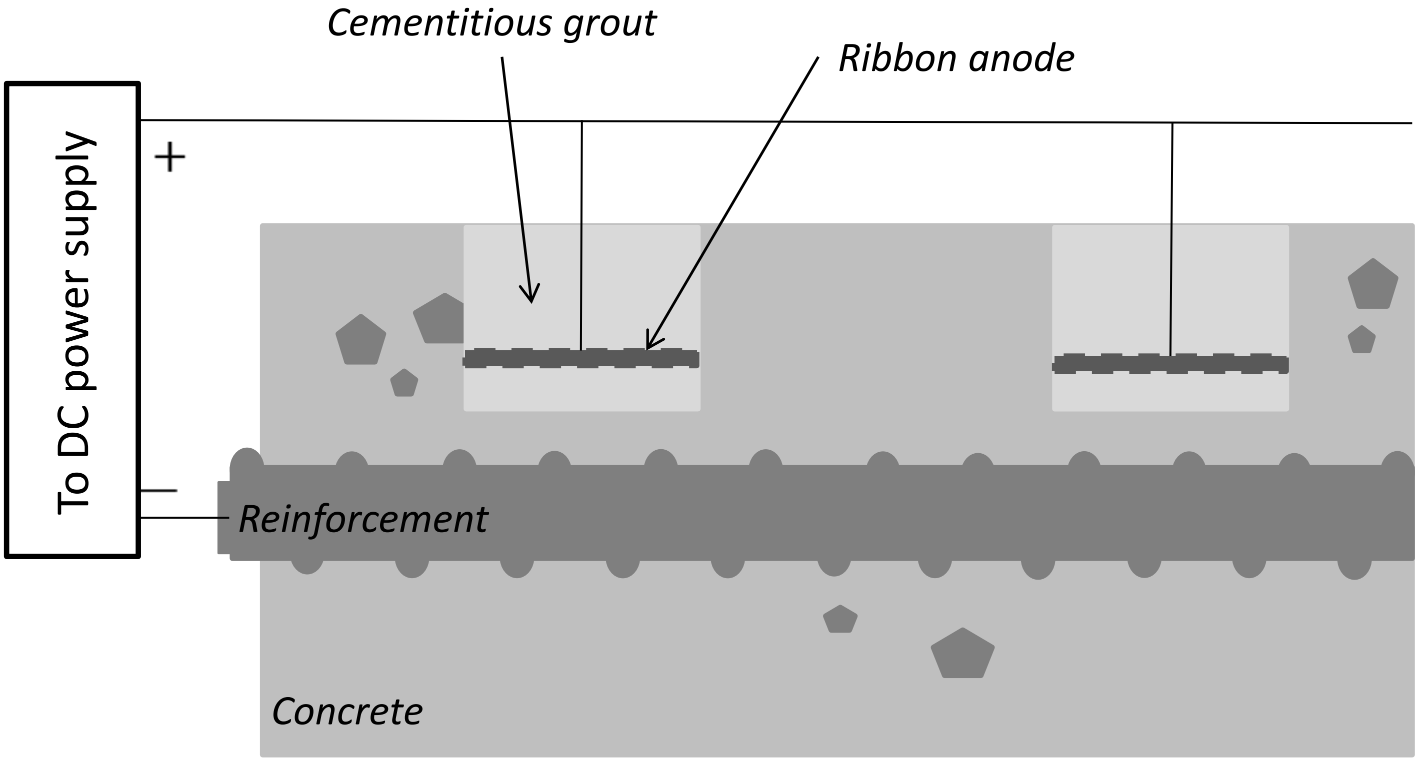

Cementitious grout
Ribbon anode
To DC power supply
+
−
Reinforcement
Concrete

(b)

Figure 10 b&w print



(a)


Cementitious grout
Ribbon anode
To DC power supply
+
–
Reinforcement
Concrete

(b)

Figure 11 colour web

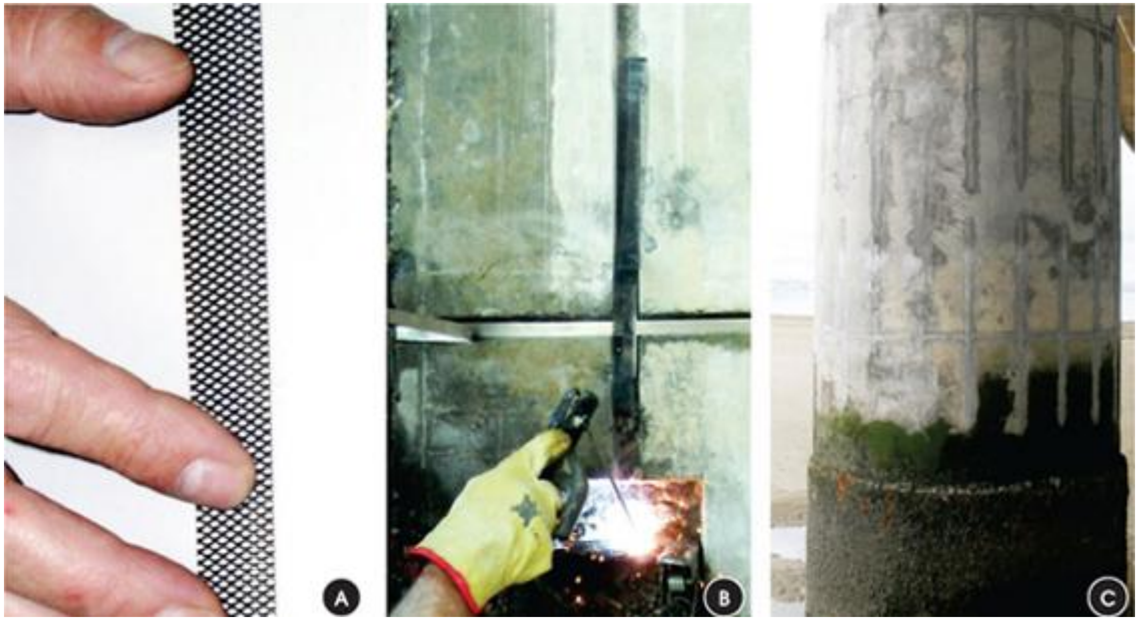


Figure 11 b&w print

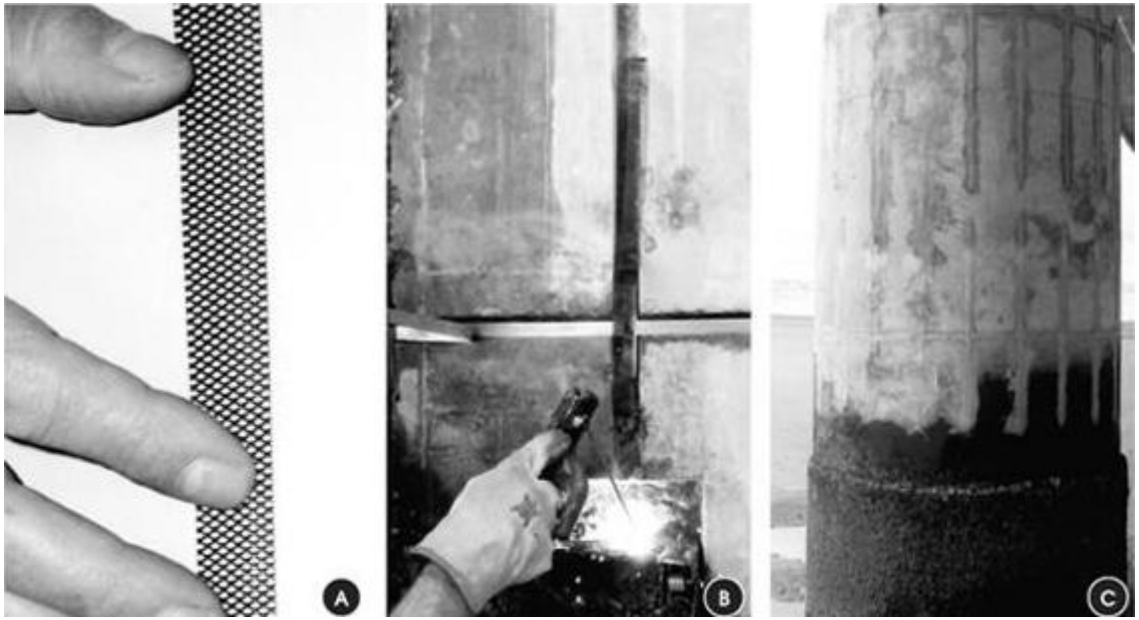


Figure 12 colour web

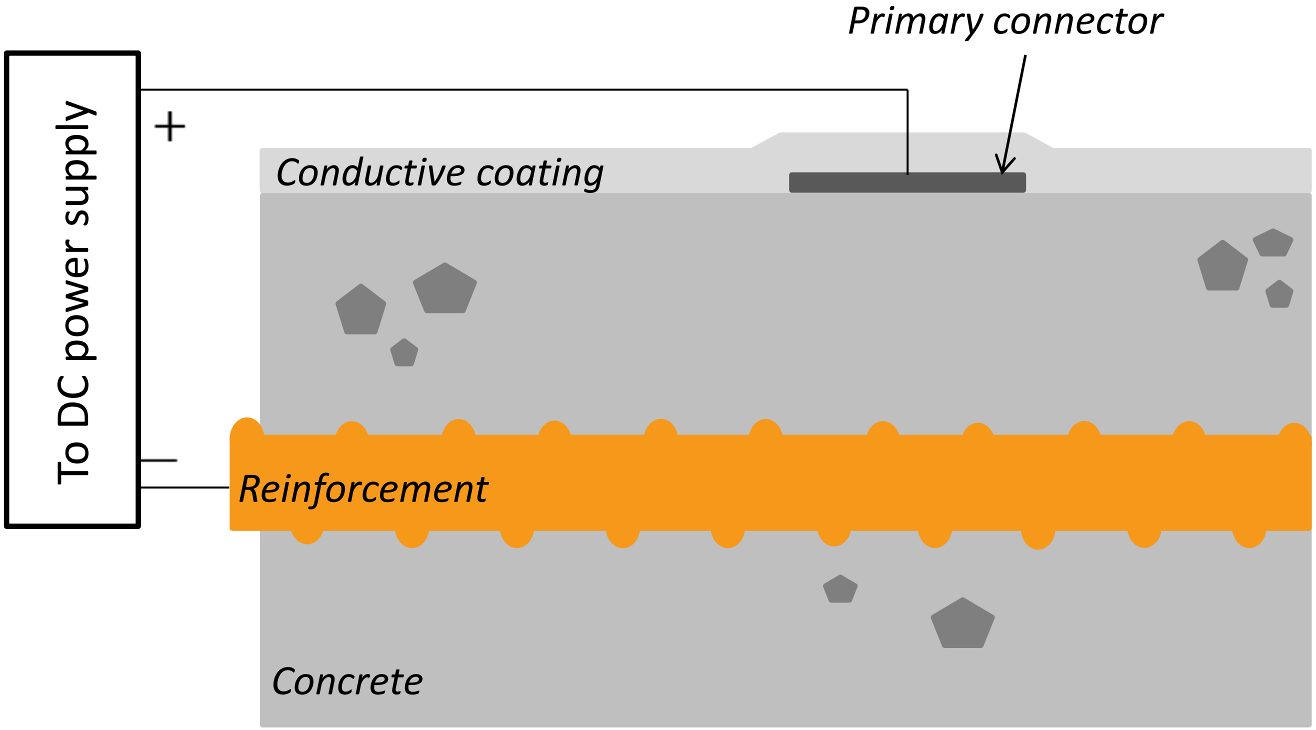


Figure 12 b&w print

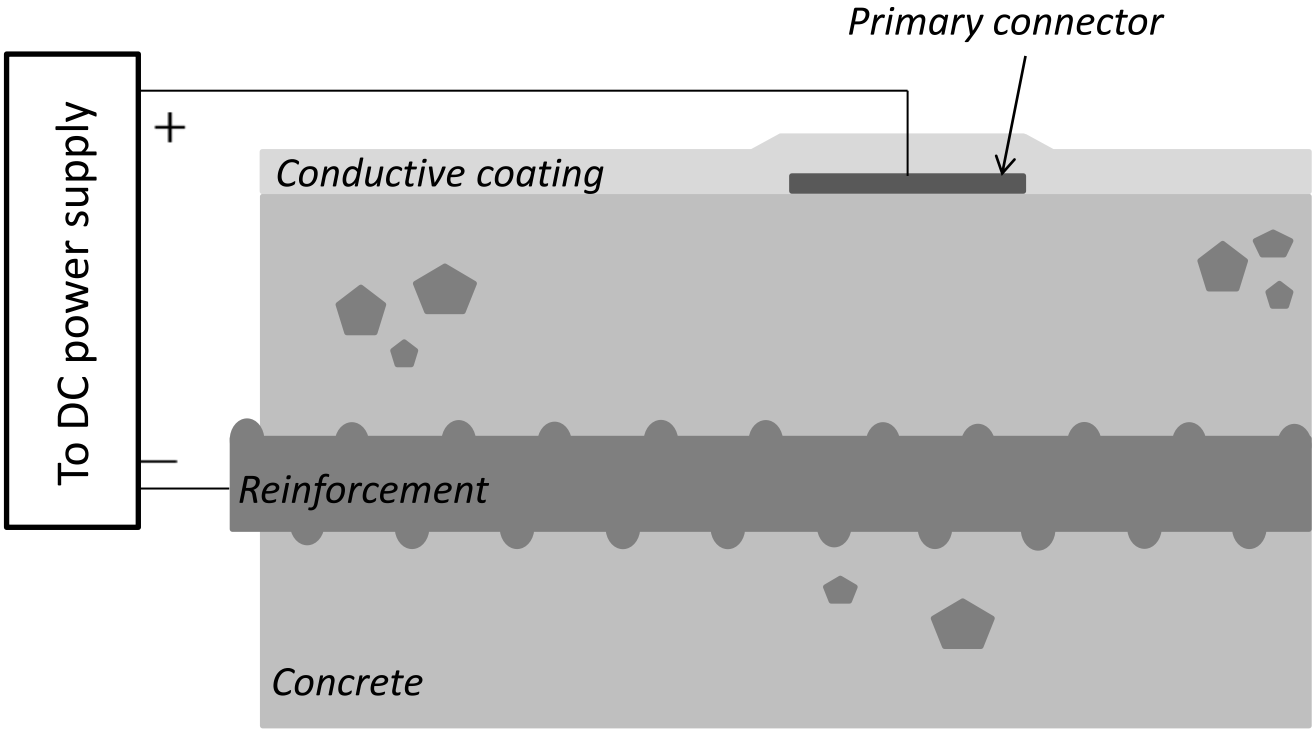


Figure 13

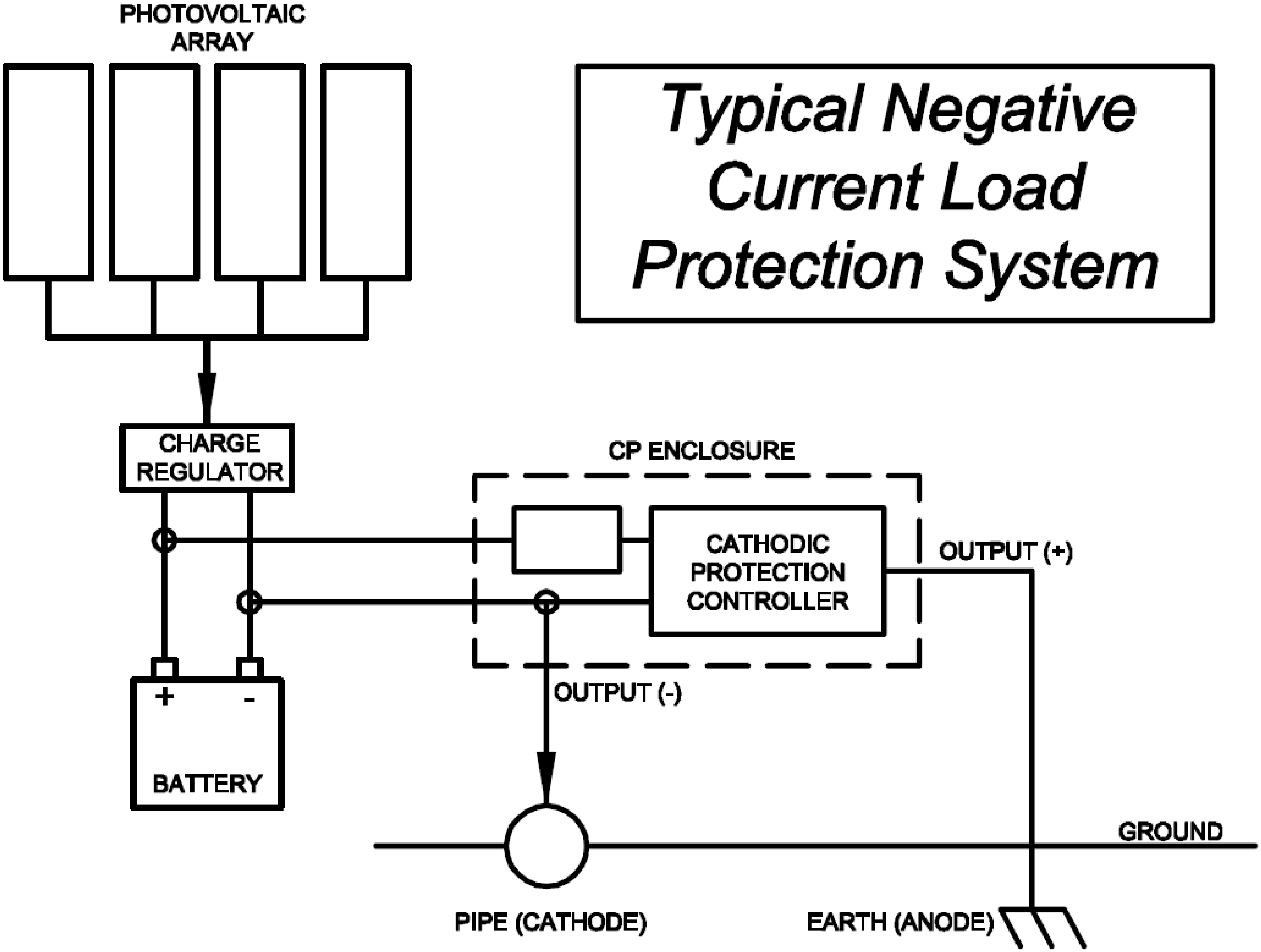

PHOTOVOLTAIC ARRAY
Typical Negative Current Load Protection System
CHARGE REGULATOR
CP ENCLOSURE
CATHODIC PROTECTION CONTROLLER
OUTPUT (+)
+
-
BATTERY
OUTPUT (-)
GROUND
PIPE (CATHODE)
EARTH (ANODE)

Figure 14 colour web

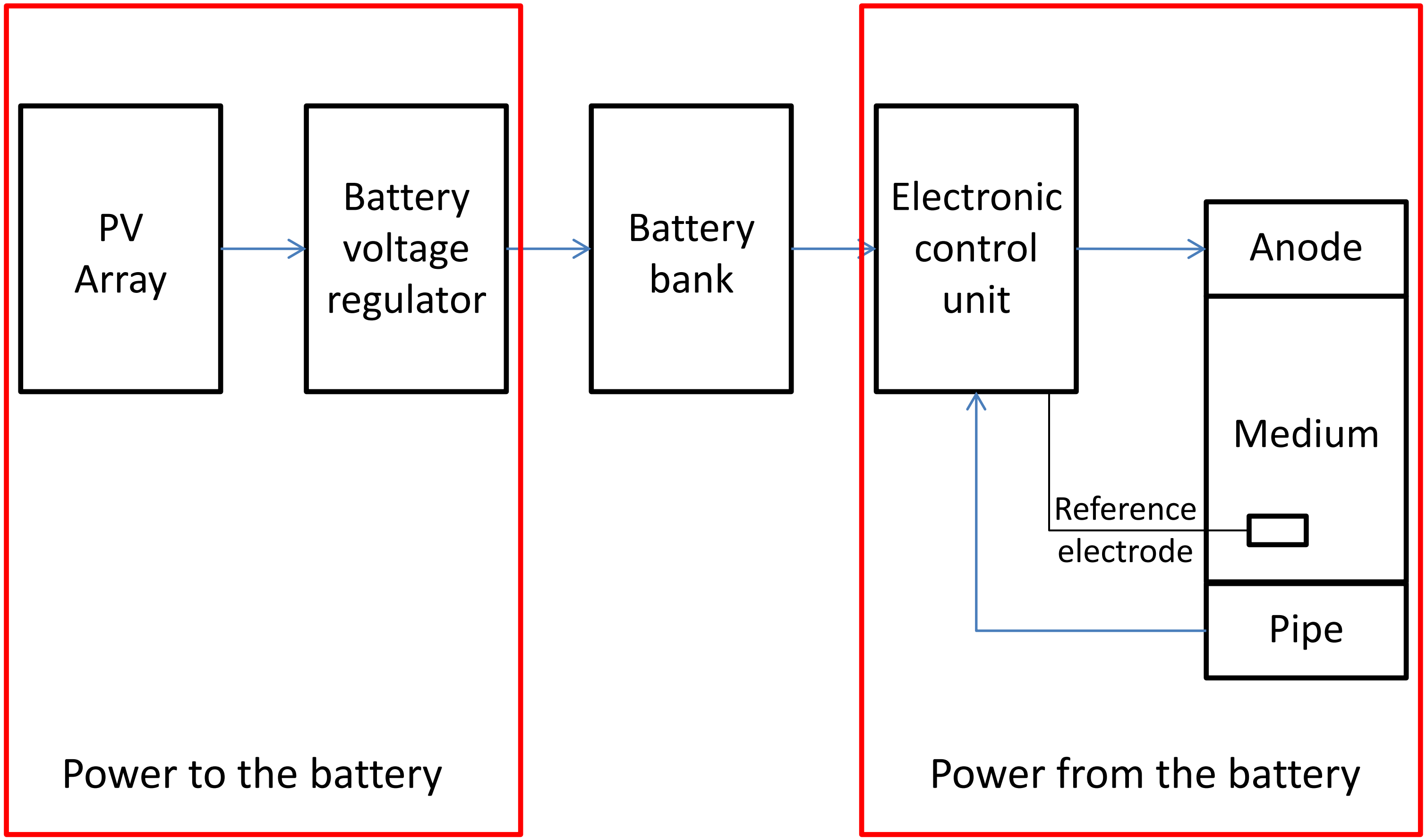


Figure 14 b&w print

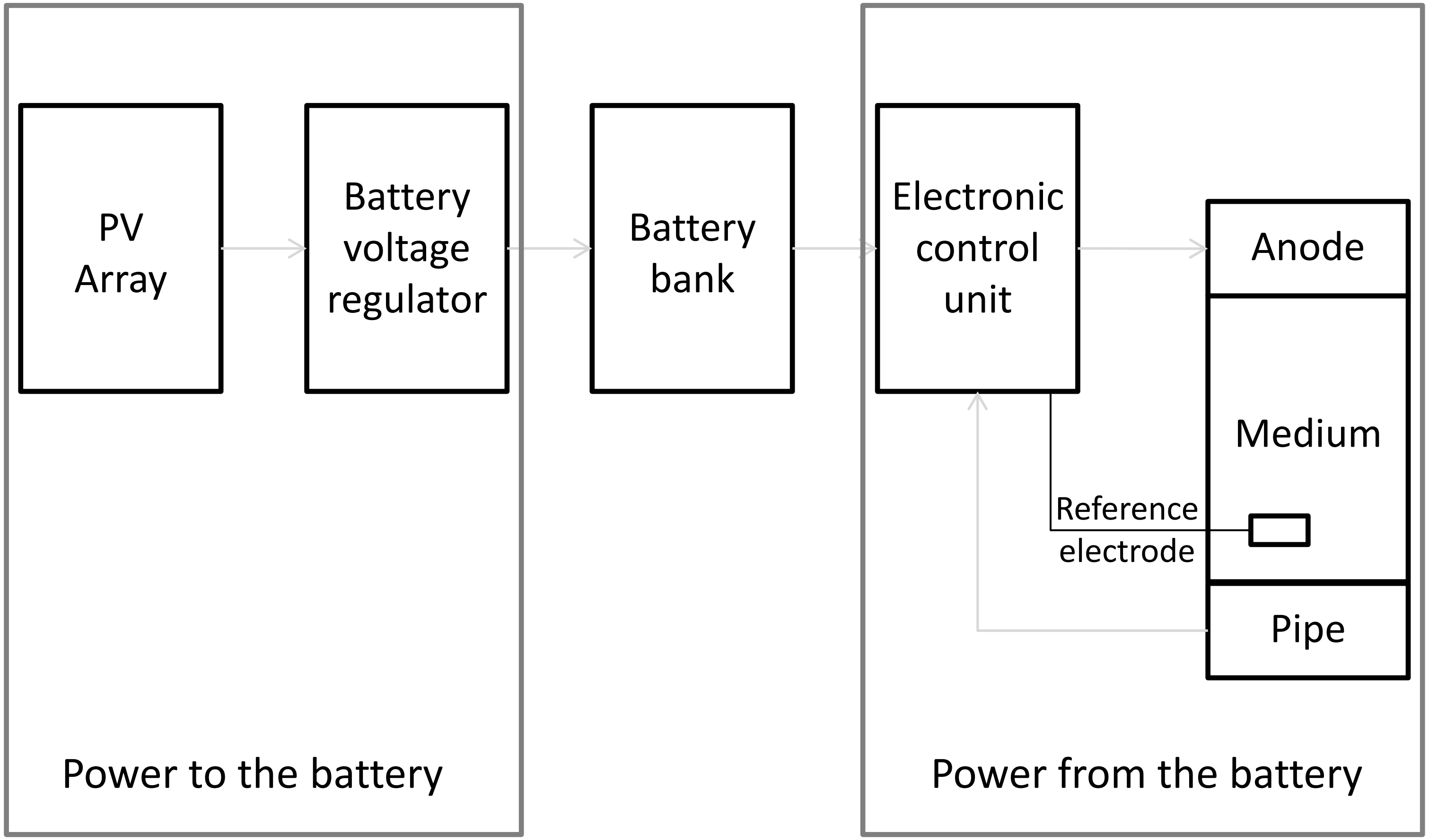


Table 1

Anode	Design	Ref.
Atmospherically exposed concrete		
Organic coatings **ICCP**	• Typical current densities 0.002-0.02 A/m^2. • 5-15yrs lifespan. A series of conductors (primary anodes) fixed to the concrete surface or integrated into the coating. The conductors distribute current within the coating. Not suitable for wet structures or wearing surfaces.	[25, 35]
Metallic coatings **ICCP/ SACP**	• Typically 0.002-0.02 A/m^2 • 10-25yr lifespan • Zn for SACP and ICCP, Al-Zn, Al-Zn-In for SACP, Ti for ICCP. Primary anodes feed connections of titanium, stainless steel or brass plates fixed to the concrete surface. One anode per 9m^2 is typical. Not suitable for wearing surfaces.	[25, 35, 39, 63]
Activated titanium **ICCP**	• Typically limited to long term max of 0.11 A/m^2. • 10-50yrs lifespan (for 0.2 A/m^2) Activated titanium anodes are coated with mixed metal oxides and embedded into the structure. Types include anodes with overlays, anodes cast into slots or drilled holes or fixed to the surface under glass reinforced plastic casing. Titanium substrate may be expanded mesh, strip, wire or tube. Suitable for wet and wearing surfaces.	[25, 35, 63]
Conductive cement materials **ICCP**	• Typically 0.002-0.02A/m^2. But may be maintained at 0.03 A/m^2 for a period of weeks. • 25+ yrs lifespan Can contain granular carbon or carbon fibres and a metallic coating as the conductive medium. The fibre system is spray applied to the prepared concrete surface.	[35, 63]
Repair/ Discrete anodes **SACP**	• 25-50 yrs lifespan For use during repairs in chloride environments. Prevents the repaired, now cathodic, reinforcement area from causing new anodic corrosion on nearby steel. Similar discrete anodes can be installed in holes cored or cut into the concrete and wired together.	[35]
Adhesive zinc sheet **SACP**	• 25-50 yrs lifespan Rolls of zinc foil are coated on one side with an ionic conductive adhesive gel (hydrogel). Applied to the prepared surface with sealed edges. May be coated.	[35]
Pile anode jackets **ICCP/ SACP**	Expanded anode mesh in permanent glass-reinforced form, grouted to the concrete piers, piles or columns. For ICCP titanium a mesh is used, for galvanic systems a zinc mesh is common.	[63]
Immersed concrete		
SACP	Normally slender stand-off or hull mounted, installed by direct welding to the embedded steel. For saline waters aluminium-zinc-indium, zinc or magnesium alloys are used (Zn and Mg also can be used for non-saline waters). Can be welded directly to the steel or connected using cabling.	[35, 63]
ICCP	• 10-30 A/m length of silicon-iron- chrome, • 0.2-0.3 A/m^2 for lead silver, • Up to 1 A/m^2 for mixed metal oxide coated titanium • Up to 3 A/m^2 for , platinized titanium or niobium Typically high silicon cast iron (with chrome in chloride environments). Available as rod, tube or strip, mounted directly on the concrete structure or nearby.	[63]
Buried concrete		
SACP	Traditional zinc or magnesium alloy anodes may be used. They can be applied directly or within a chemical backfill (typically gypsum, benyonite and sodium sulphate). They are normally connected to the embedded steel.	[35]
ICCP	• 1-2A for a single anode • 5A-200A for clustered ground beds • 10-100A for deep vertical ground beds Typically high silicon cast iron (with chrome if in a chloride environment), graphite or mixed metal –oxide-coated titanium. Magnetite and scrap iron are other options. They can be installed either as single anodes or together to form a vertical or horizontal lines. The anodes are embedded in the conductive backfill.	[35]

Table 2

	Advantages	***Disadvantages***
SACP	• Can prove adequate in places where the concrete resistance is low • Simpler to design and install • Independent of external power source • Less liable to cause interaction on adjacent structures • No need for a control system • Less risk of hydrogen embrittlement on pre-stressed steel	• Less common with reinforced concrete (not as much performance data available) • Unable to control the current output • Unknown degree of protection provided • May need to add anodes if the current requirements change • Shorter lifespan for the anode • Current is not adequate in high resistance environments
ICCP	• Much more commonly used with reinforced concrete, better understood and greater experience of installers/designers/inspectors • Can control the current to accommodate variations in exposure conditions or chloride contamination • Can be used in high resistance environments • Current output is controllable and flexible	• Need for ongoing DC power supply (currently from fossil fuels) • Transformer-rectifier, monitoring systems and their enclosure are vulnerable to damage and atmospheric corrosion • Care must be taken to minimise interaction with other structures • Greater risk of hydrogen embrittlement which is dangerous in pre-stressed steel.