Distributed Galvanic Anode Performance on Bridges in the U.S.

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Over time, concrete bridges exposed to de-icing chemicals and marine environments may develop reinforcing steel corrosion. If unchecked, chloride-induced corrosion leads to increased maintenance needs and structural problems. Severe corrosion often necessitates costly structure replacements, causing public access disruption. Yet, with proper repair strategies and corrosion management, structures can be rehabilitated, strengthened, and their service life extended more sustainably than replacement. Distributed galvanic anodes, applied to corroding abutments, columns, and beams, offer effective, low-maintenance cathodic protection (CP). Monitored field applications show they can provide more than 20 years of efficient and sustainable service life extension.

Embedded galvanic anodes designed to protect reinforcing steel in chloride-contaminated, concrete-adjacent concrete "patch" repairs were developed in the late 1990s.[1] The original concrete anode was puck-shaped and consisted of high-purity zinc encased in a mortar formulated with high-porosity and lithium hydroxide to maintain a pH greater than 14 to keep the zinc active over the life of the anode. This approach of a high-pH mortar around the zinc to prevent anode passivation is commonly referred to as alkali-activation.

This generation of anode has been referred to as a discrete or point anode where individual anode units are spaced out in a linear fashion along the interface of new and existing concrete, or in a grid formation if a broader area of protection is required. Twenty-plus years of performance data from these anodes has been collected, providing a thorough understanding of the capabilities of these anodes and how they age over time.[2]

The primary advantage of galvanic anodes is their simplicity. Once the anodes are installed and connected to the steel, they operate naturally based on the difference in potential between the anode and the reinforcing steel. No other electrical components that need to be monitored or maintained, such as rectifiers, are required. However, if an owner or engineer would like to collect performance information, additional wiring and equipment can be installed to monitor galvanic anodes. Monitoring options can range from a simple system consisting of a junction box with a shunt to measure generated current to more complex systems capable of collecting current and polarization data remotely. The primary disadvantages of galvanic anodes are their fixed driving potential and anode consumption over time.

Shortly after the introduction of the discrete anode for repair, a cylindrical-shaped galvanic anode based on the same alkali-activated technology was introduced. This new configuration allowed galvanic anodes to be placed into drilled or cored holes in sound concrete. One of the earliest documented applications for the cylindrical-shaped anodes in the United States was their installation into residential building balconies along the Florida coastline.[3]

Today, these two types of embedded galvanic anode systems are described in the literature as Type 1 (discrete anodes for concrete repair) and Type 2 (discrete anodes for sound concrete). Type 1 anodes are used to extend the life of standard concrete repairs by protecting reinforcement that remains in chloride-contaminated concrete around the concrete repairs where future corrosion can occur. Type 2 anodes are installed in a grid orientation for general corrosion protection or used to target active corrosion sites as identified by a half-cell corrosion potential survey (ASTM C876). The methods of keeping the anode from passivating are generally described as alkali-activated and halide-activated.[4]

Distributed Galvanic Anodes

Another form of alkali-activated anode, distributed galvanic anodes, was introduced in 2003. Distributed galvanic anodes utilize the same basic technology as discrete anodes but are different in shape and application. They can include a zinc core with paste or a porous mortar containing sufficient lithium hydroxide to prevent passivation for the expected service life of the anode. Like the Type 1A and Type 2A alkali-activated discrete anodes, the lithium hydroxide activator is corrosive to zinc but not to reinforcing steel, thus meeting the requirement of concrete repair codes that prohibit repair materials from containing added constituents that are corrosive to reinforcing steel.[5]

These anodes are custom manufactured in lengths from 0.9 to 2.3 m (3 ft to 7.5 ft) with varying zinc mass and zinc surface areas. Zinc mass can be customized as required for the application. Historically, the zinc mass is typically in the range of 113 to 907 g (0.25 to 2.0 lbs) of zinc per linear foot of anode. Distributed anodes may also utilize an outer layer of zinc foil and plastic mesh. Distributed galvanic anodes also have been referred to as ribbon anodes, strip anodes, rod anodes, linear anodes, distributed sacrificial anodes, and distributed anode systems.

Distributed anodes can be used in a linear orientation where they are placed end-to-end in expansion joint repairs, joint closures, deck widening projects, and concrete repairs. Using distributed anodes in these types of applications provide more consistent current distribution along the new/old concrete interface compared to Type 1 discrete anodes. Additionally, distributed anodes offer greater surface area and zinc mass, which results in improved performance. Especially with heavily reinforced structures, distributed anodes are likely to be significantly more economical than discrete anodes.

FIGURE 1 Galvanic encasement of abutment using distributed galvanic anodes, Sidney, Ohio.

To protect larger areas, distributed anodes can be installed in a parallel orientation across the structure. They can be installed into slots or more commonly covered with a concrete jacket or overlay, referred to as galvanic encasement. Prior to anode installation, the deteriorated concrete is removed, and the exposed reinforcing steel is cleaned. The anodes are attached to the reinforcing steel and covered with concrete, thus completing the concrete repair and corrosion protection in a single step. Additional reinforcement can be provided with conventional reinforcing steel or noncorrosive fiberglass reinforcement in the overbuilt section.[6] If conventional steel is used, it should also be accounted for in the CP design.

Ohio DOT Galvanic Encasement Abutment Repairs

The Ohio Department of Transportation (ODOT) was experiencing an aggra-

TABLE 1 GALVANIC CATHODIC PROTECTION SYSTEM PERFORMANCE SUMMARY

Date	Temperature, degree C	On Potential E_{ON}, mV	Instant Off E_{IOFF}, mV	Current Density Icp, mA/m^2	Polarization Epol, mV
5/6/2005	(*Native*)		*-654*	37.7	
7/20/2005		-1061	-990	14.0	346
8/16/2005	30.6	-1136	-998	12.7	344
10/26/2005	12.2	-1082	-1023	5.4	369
12/7/2005	10.6	-982	-964	2.9	310
5/1/2006	13.9	-1051	-967	7.3	313
12/20/2006	4.6	-1176	-1113	3.7	459
5/30/2007	26.3	-1212	-1104	7.5	450
9/20/2007	23.9	-1238	-1136	9.1	482
12/19/2008	4.4	-1174	-1105	3.5	451
7/9/2009	23.3	-1146	-1125	2.8	471
5/11/2010	12.2	-1160	-1139	3.4	485
10/16/2011	22.2	-1193	-1142	5.9	488
4/22/2013	21.1	-1113	-1079	3.1	425
3/24/2015	1.7	-1060	-1035	2.0	381
9/17/2008	25.6	-1044	-1007	5.3	353
9/9/2020	26.7	-1036	-1005	3.6	351
8/23/2022	26.7	-1008	-986	2.0	332

vating corrosion problem with its slab bridge abutments. Leaking expansion joints over the abutments were causing chloride-induced corrosion of the abutment, and their repairs were only lasting five to seven years.

In response, ODOT implemented a galvanic encasement repair design that utilized a built-out section with distributed galvanic anodes and additional epoxy coated reinforcing (Figure 1). The distributed anodes are connected to the existing conventional reinforcing to mitigate corrosion in the existing element that is being encased. A major advantage of this new repair detail is that the abutment is repaired, protected, and strengthened while staying in service. Numerous bridges were repaired in this manner and are still in great shape a decade later.

A bridge abutment on Interstate 75 near Sydney, Ohio, USA was repaired using the ODOT galvanic encasement technique in July 2005. The abutment is approximately 15.8 m wide by 1.2 m high (52 ft wide by 4 ft high). One zone of distributed anodes was installed with the ability to monitor the anode performance as part of an ODOT technology evaluation program.

On the south abutment of the southbound bridge, three 1.8 m (6 ft)-long anodes with 680 g (1.5 lb) zinc per anode were installed to provide CP and wired so that they could be monitored. The remaining anodes installed on the abutment were directly connected to the reinforcing steel. Current and temperature data were collected by battery-powered dataloggers and downloaded manually on a periodic basis. Manual measurements of the entire abutment surface were obtained periodically.

The anodes have been installed and monitored for more than 17 years. A visual inspection in 2022 showed that the condition of the repaired abutment is still very good. The system performance data (Table 1) indicates that the galvanic CP system installed is performing excellently with instant off potentials more negative than -850 mV CSE and polarization shifts exceeding 100 mV.

Concrete CP criteria have been established by NACE International (now AMPP), British, and European standards organizations. The relevant NACE publication that provides guidance regarding CP criteria is *NACE SP0216, "Sacrificial Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*." NACE SP0216 defines the criteria for CP as:

- The potential of the steel in concrete is more negative than -720 mV versus a copper/copper sulfate reference electrode (CSE) with the sac-

FIGURE 2 New distributed anode cathodic protection jackets installed, Lake Worth, Florida.

TABLE 2 PERFORMANCE OF ALKALI-ACTIVATED DISTRIBUTED ANODES ON MARINE COLUMNS ABOVE THE TIDAL ZONE

Bridge	Column	Current (mA)	Native at Construction 4/2015 (mV vs. CSE)	Instant Off Potential (mV vs. CSE)	Depolarization Potential 68 h (mV vs. CSE)	Polarization after 68 h of Decay (mV)	Polarization Compared to Native (mV)	Does the Pile Meet CP Criteria per NACE SP0408
WB	1	149	-268	-760	-691	69	492	Yes
WB	2	180	-202	-570	-380	190	368	Yes
WB	3	140	-203	-550	-460	90	347	Yes
WB	4	145	-202	-710	-520	190	508	Yes
WB	5	70	-260	-622	-590	32	362	Yes
WB	6	126	-285	-830	-630	200	545	Yes
WB	7	60	-309	-1064	-815	249	755	Yes
WB	8	45	-304	-955	-560	395	651	Yes
WB	9	50	-349	-630	-506	124	281	Yes
WB	12	124	-320	-770	-480	290	450	Yes
WB	13	85	-298	-1043	-739	304	745	Yes
WB	14	55	-392	-959	-760	199	567	Yes
WB	15	133	-260	-618	-496	122	358	Yes
WB	16	90	-399	-870	-775	95	471	Yes
WB	17	122	-388	-882	-720	162	494	Yes
WB	18	110	-382	-1069	-774	295	687	Yes
WB	19	95	-355	-1045	-730	315	690	Yes
WB	20	114	-276	-698	-430	268	422	Yes
EB	1	150	-266	-748	-530	218	482	Yes
EB	2	179	-328	-755	-580	175	427	Yes
EB	3	120	-200	-563	-430	133	363	Yes
EB	4	122	-285	-883	-630	253	598	Yes
EB	5	40	-237	-609	-560	49	372	Yes
EB	6	154	-329	-654	-527	127	325	Yes
EB	7	55	-330	-802	-650	152	472	Yes
EB	8	59	-356	-808	-499	309	452	Yes
EB	9	45	-343	-603	-466	137	260	Yes
EB	12	32	-363	-681	-524	157	318	Yes
EB	13	51	-319	-827	-670	157	508	Yes
EB	14	65	-282	-990	-782	208	708	Yes
EB	15	55	-365	-991	-780	211	626	Yes
EB	16	60	-371	-929	-724	205	558	Yes
EB	17	145	-388	-949	-739	210	561	Yes
EB	18	100	-358	-1039	-780	259	681	Yes
EB	19	89	-330	-996	-660	336	666	Yes
EB	20	99	-218	-600	-419	181	382	Yes

100	mV- NACE cathodic protection polarization criterion achieved
-200	mV vs CSE- NACE cathodic protection passivation criterion achieved
-850	mV vs CSE- NACE Instant Off potential criterion achieved

Note 1: Only one of the NACE criterion needs to be achieved to pass SP0408 for a protected structure

FIGURE 3 Surface-mounted distributed anode field study, Louisville, Kentucky.

rificial anode disconnected.

- A minimum of 100 mV of polarization should be achieved at the most anodic location, typically in each 50 m^2 (500 ft^2) area or zone, or at artificially constructed anodic sites, provided its corrosion potential, or decayed off-potential is more negative than -200 mV vs. a CSE. If the corrosion potential or decayed off-potential is less negative than -200 mV CSE, then the steel is passivated, and no minimum polarization is required.

Using the anode current data and initial zinc mass, the estimated anode life can be estimated using Faraday's equation. The anode life for the Sydney, Ohio, bridge is estimated at 35 years, substantially exceeding the original 15-year design. This calculation includes an anode utilization factor of 0.8 and an anode efficiency factor of 0.9.

Florida DOT Jacketing With Distributed Anodes

The Lake Avenue Bridge over the Intercoastal Waterway in Lake Worth, Florida, USA is comprised of two bridges: an eastbound and a westbound structure. The Lake Avenue Bridge's substructure is comprised of flattened, oval-shaped, reinforced concrete columns supported on footers and piles. The columns measure 1.2 m (4 ft) wide by 2.1 m (7 ft) long, with 0.9 m (3 ft) of flat section in the center and 0.6 m (2 ft) of curved sections on each end.

Each of the bridges have 20 piers with a single column at each pier. These Florida Department of Transportation (FDOT) marine bridges were suffering from corrosion due to chloride contamination from storm surges and atmospheric exposure. Due to the corrosion deterioration of the columns, galvanic CP jackets with alkali-activated distributed anodes were installed in 2015 on a total of 36 columns.

The scope of work included the removal of existing 2.1 m (7 ft)-high structural steel jackets, removal of deteriorated concrete, and installation of the new CP jackets of the same height.

Florida DOT typically uses CP jackets with bulk anodes for concrete pile protection. In this case, the bases of the columns are not normally submerged in the seawater, so a different approach was taken. The FDOT specification required that the activated distributed anodes be pre-attached to the fiberglass forms at a spacing of 0.3 m (12 in). Welded wire fabric was also installed in the 100 mm (4 in) annular space of each jacket between the pre-attached anodes and the concrete surface. After the concrete fill cured, a potential monitoring access port was installed in each jacket (Figure 2).

In May 2022, the CP jackets were evaluated after seven years of continuous operation (Table 2). The conclusion of the evaluation is that the alkali-activated distributed anodes are performing as intended, with the anodes providing sufficient current to polarize the steel rebars, meet the NACE CP standard, and mitigate active corrosion.

Kentucky Transportation Cabinet Surface-Mounted Distributed Anodes

More recently, a field study demonstration of a new surface-mounted distributed anode system was installed on a beam in the summer of 2022 in Louisville, Kentucky, USA. The selected beam was chloride-contaminated from deicing-contaminated water leaking through the deck joint above the beam. The beam exhibited characteristics of highly active corrosion as determined by a corrosion potential survey and concrete chloride content testing.

Different sizes of alkali-activated, surface-mounted galvanic anodes were installed on the concrete surface (Figure 3). After the concrete surface was prepared, the individual anode units were installed in parallel horizontal rows across the beam face. A conductive cementitious mortar was used to bond the anodes to the concrete and create an ionic connection to the beam. The anode units were further secured with mechanical anchors. A remote monitoring system was installed to measure the galvanic current output of the anodes, ambient temperature, and potential of the reinforcing steel using an embedded reference electrode.

The preliminary results are encouraging. After almost five months of monitoring, the data show that the anodes are producing sufficient galvanic current to provide corrosion mitigation, the current fluctuates with temperature and rain events, and the current density is sufficient to polarize actively corroding reinforcing steel to meet or exceed the NACE 100mV polarization criteria (Figure 4).

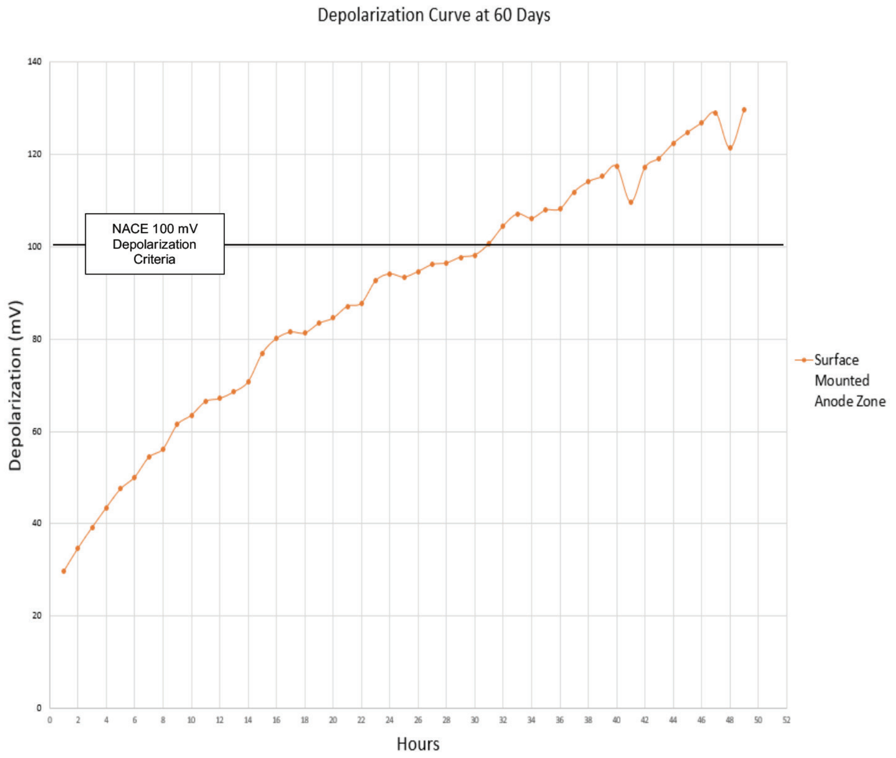

FIGURE 4 Depolarization Curve 60 Days After Energizing.

Summary

Alkali-activated distributed anodes have been used on reinforced concrete bridges throughout the United States for almost 20 years. The anodes have been used in a variety of environments ranging from Northern states with corrosive de-icing salts to marine exposure in Southern states with tropical climates. Long-term monitoring has demonstrated that the anode systems can be designed to satisfy NACE CP criteria while providing low-maintenance CP for up to 35 years.

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References

1 G. Sergi, C.L. Page, "Sacrificial anodes for cathodic protection of reinforcing steel around patch repairs applied to chloride-contaminated concrete," *Proc. Eurocorr '99*, European Corrosion Congress, Aachen, Germany.

2 D. Whitmore, G. Sergi, "Long-term Monitoring Provides Data Required to Predict Performance and Perform Intelligent Design of Galvanic Corrosion Control Systems for Reinforced Concrete Structures," CORROSION 2021, paper no. 16712 (Houston, TX: AMPP 2021).

3 J.C. Ball, D.W. Whitmore, "Corrosion Mitigation Systems for Concrete Structures," *Concrete Repair Bulletin*, July/August 2003, pp 6-11 (ICRI: St Paul, MN).

4 ACI Committee E706, "RAP Bulletin 8: Installation of Embedded Galvanic Anodes," American Concrete Institute, Farmington Hills, MI, p. 4.

5 ACI Committee 562, "Assessment, Repair, and Rehabilitation of Existing Concrete Structures–Code and Commentary," American Concrete Institute, Farmington Hills, MI.

6 J.C. Ball, D.W. Whitmore, "Embedded Galvanic Anodes for Targeted Protection in Reinforced Concrete Structures," *Concrete Repair Bulletin*, January/February 2009, pp 6-9 (ICRI: St. Paul, MN).

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