Independent Hybrid Corrosion Protection Appraisal

On behalf of:

Concrete Preservation Technologies Ltd.

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DuoGuard™ Hybrid Anode™ Site Performance Review

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1. INTRODUCTION

AECOM were commissioned by Concrete Preservation Technologies (CPT) Ltd. to undertake an independent appraisal of the site performance of DuoGuard™ Hybrid Anode™ systems installed on 6 bridge structures located throughout the UK. The following bridge structures are included within this report:

1. Kyle of Tongue, Achuvoldrach;
2. Whiteadder, Berwick;
3. Laverock Hall, Newcastle;
4. Storth Lane, South Normanton;
5. Paston Interchange, Peterborough;
6. M69 junction 2, Huncote, Leicester.

The independent appraisal for each structure includes:

- Details of the structure and installed anode system;
- The current extent of deterioration (if any) following a visual inspection;
- Recorded steel potential readings and corrosion rate measurements;
- A structure corrosion risk assessment;
- Recommendations that could improve the functionality of the system.

2. HYBRID ANODE SYSTEM

The DuoGuard™ Hybrid Anode™ is used as both an impressed and galvanic system to arrest the initiation of corrosion. Initially, the system is connected to a temporary, constant voltage, power supply typically for a period of at least one week, depending on the type of reinforcement (i.e. mild steel or prestressed), to deliver a charge to the reinforcing steel. This initial treatment phase re-passivates the areas of steel reinforcement subject to corrosion by means of generating a reservoir of alkali at the steel concrete interface.

The hybrid anode is then disconnected from the temporary power supply and connected directly to the steel reinforcement in a galvanic phase. This treatment phase continues for the remainder of the anodes' working life and distributes a relatively low current to the steel reinforcement to maintain the passive layer at the steel surface.

The hybrid technology offers the same advantages of a galvanic system in that little or no maintenance is required throughout its design life cycle and that no permanent power supply needs to be installed as part of the works. The hybrid technology provides the added benefit of the initial treatment phase to improve the condition of the steel and arrest on-going corrosion.

The hybrid anode system design can allow for an additional impressed current phase at a later stage in the structure's life if any corrosion activity is detected through monitoring of the corrosion rates of the reinforcing steel. This provides the benefit of extending the life of repaired areas by re-establishing steel passivity.

3. METHODOLOGY

The following methodology has been applied for each structure in order to effectively undertake an independent appraisal of the performance of the hybrid anode systems examined:

- Review as-built drawings and historic structure information;
- Review previous principal inspection reports and specification documents;
- Review previous monitoring data;
- Conduct a visual inspection of the structure;
- Hammer tap survey;
- Take photos of the structure and monitoring equipment;
- Produce a technical note with inspection findings and, where available recorded defects (if any);
- Record steel potential readings with the system turned on and then start the de-polarisation process;
- Record de-polarised steel potential readings;
- Review calculated corrosion rates in accordance with performance monitoring criteria detailed in Section 3.
- Make observations on the data and subsequently discuss trends in detail;
- Provide recommendations to the client that could potentially improve the functionality of the system

4. CRITERIA FOR PERFORMANCE MONITORING

The performance for impressed current cathodic protection systems require a positive depolarisation shift of steel potentials by 100mV or more over a certain timeframe to comply with the protection criteria (ISO 12696:2012). Investigations and research into the behaviour of galvanic and hybrid systems have shown that the 100mV potential shift is not always achieved in benign environments or when the risk of corrosion has been reduced by the anode system itself. The following literature provides detailed information on the ‘responsive behaviour’ of galvanic and hybrid anodes:

- Christodoulou, C. Goodier, C. Austin, S. Webb, J. Glass, G. 2013. Hybrid corrosion protection of a prestressed concrete bridge. European Corrosion Conference 2013, *EUROCORR 2013*, Estoril, Portugal, 1st-5th September 2013.

- Holmes, S.P. Christodoulou, C. Glass, G.K. 2013. Monitoring the passivity of steel subject to galvanic protection. *Corrosion & Prevention 2013*, Australasian Corrosion Association, Brisbane, Australia, 10th-13th November 2013, paper 133. 11pp.

- Glass, G. Christodoulou, C. Holmes, S. 2012. Protection of steel in concrete using galvanic and hybrid electrochemical treatments. In: Alexander, M.G. Beushausen, H.D. Dehn, F. Moyo, P. (eds). 2012. *Concrete Repair, Rehabilitation and Retrofitting III:* 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-3, 3-5 September 2012, Cape Town, South Africa. pp. 523-526. Taylor and Francis Group.

- Holmes, S.P. Wilcox, G.D. Robins, P.J. Glass, G.K. Roberts, A.C. 2011. Responsive behaviour of galvanic anodes in concrete and the basis for its utilisation, *Corrosion Science*, Vol. 53, pp. 3450–3454.

ISO 12696:2012 allows the use of alternative criteria for hybrid and galvanic systems, stating that, ‘*passive steel is indicated by a corrosion rate of less than 2mA/m² and preferably less than 1mA/m². A falling trend in corrosion rate combined with a rising trend in corrosion potential is also a sign that protection is being achieved’*.

A corrosion rate of this magnitude relates to a reinforcing steel section loss of approximately 1mm over 500 years. This report provides a summary of the steel depolarisation readings recorded, however it focuses primarily on the calculated corrosion rates and the effectiveness of the anode systems to prevent corrosion initiation.

5. KYLE OF TONGUE, ACHUVOLDRACH

5.1 Structure Details

The Kyle of Tongue Bridge forms part of the Kyle of Tongue causeway and carries the A838 over the Kyle of Tongue sea loch on the North coast of Scotland. The bridge was fully refurbished in 2011 following reports of high chloride concentrations due to the exposure in a marine environment and de-icing salts used on the bridge deck during the winter months.

The 183 metre long bridge, built in 1971 to replace a ferry crossing takes the form of 17 simply supported spans with each compromising of 16 pre-stressed concrete beams spanning between 17 reinforced concrete crosshead beams (pile caps) and supporting steel columns (piles). The bridge deck is constructed from a concrete infill between the pre-stressed beams. The location plan view and the elevation view, looking South towards the Ben Loyal peak, are shown in Figures 1 and 2 respectively.

Figure 1 - Kyle of Tongue Bridge, Achuvoldrach

Figure 2 - East elevation view of the Kyle of Tongue Bridge

5.2 Hybrid Anode Details

DuoGuard™ 175 anodes were installed in localised repair areas along the pre-stressed beams. Hybrid corrosion protection was provided only in areas exhibiting physical deterioration. The hybrid CP system was chosen on the basis that corrosion protection would be achieved without the need for future maintenance and based on a 30 year design life. The cross section of the bridge deck and pre-stressed beams is shown in Figure 3. Approximately 675 DuoGuard™ anodes were installed in localised repair areas during the refurbishment of the bridge which was completed in November 2011. The arrangement and installation of the hybrid anode system can be seen in Figures 4 and 5 respectively.

A requirement of the refurbishment specification was to maintain a steel potential more positive than -900mV to prevent hydrogen embrittlement of the pre-stressed strands. A combination of galvanic and hybrid systems were used to achieve this requirement.

To regulate the current output of the hybrid anodes a specially designed voltage and current controller was installed during the temporary impressed current phase along with permanent MN15 reference electrodes to monitor steel potentials. Permanent junction boxes were installed at parapet level to allow manual monitoring (Figure 6).

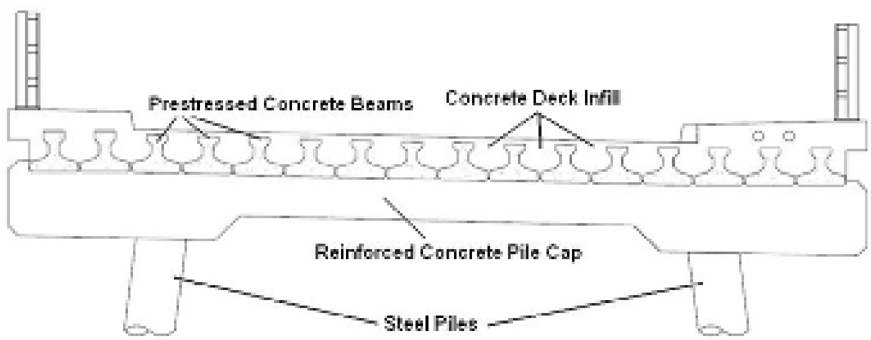

Figure 3 - Typical cross section of bridge deck

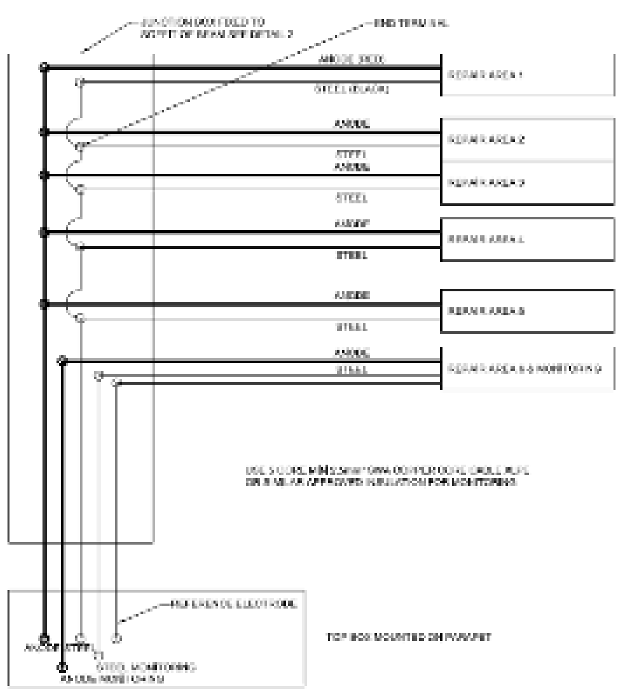

Figure 4 - Schematic layout for the installation of the hybrid anode system in the pre-stressed concrete beams

Figure 5 - Installation of Hybrid anode system in pre-stressed concrete beams

Figure 6 - General view of permanent monitoring location at parapet level

5.3 Visual Inspection

A visual inspection was carried out on 6th to 10th August 2012 by AECOM which found little or no signs of corrosion following the refurbishment in 2011. The repairs to the pre-stressed beams and pile caps were found to be in generally good condition with no signs of further delamination or spalling and no faults were indentified with the connections of the hybrid anode system at the junction box locations. An additional visual inspection was carried out in February 2013 again by AECOM as part of the final defects inspection, which did not identify any defects related to the hybrid CP system.

5.4 Review of Record Monitoring Data

Steel potential readings and depolarisation results have been monitored by AECOM at four distinct locations (Bridge spans: 8-9, 9-10, 12-13 and 16-17) since January 2012 through to March 2014. A summary of the depolarisation results and calculated corrosion rates is provided in Tables 1 and 2 respectively.

The monitoring data in Table 1 obtained from 12th January 2012 to 24th March 2014 shows more than 10 negative steel potentials generally decrease, while "off" steel potentials are moving towards positive values. There is also a gradual decrease in the current output and the magnitude of depolarisation over time. The calculated corrosion rates of the reinforcing steel (Table 2) reduced significantly after 3 to 4 months of anode installation as shown by the depolarisation results taken on 12th January 2012. The corrosion rate has continued to stay below 2mA/m² except for one occasion on 23rd September 2013 when the corrosion rate increased to 2.40mA/m² at junction box 2 (span 9-10).

5.5 Corrosion Risk Assessment

The steel depolarisation readings and calculated corrosion rates shown in Tables 1 and 2 respectively suggest that the hybrid anode system installed at Kyle of Tongue Bridge is performing satisfactorily. The general measurement in steel potentials over time moves towards more positive values, the reduction in corrosion rate and in anode output indicates steel is in passive condition. Generally, the hybrid system installed on Kyle of Tongue Bridge is characterised by very low depolarisation values. This may be associated with the generally benign environment and the overall passivity of the reinforcement. When such low depolarisation values are recorded, care should be exercised to ensure measuring equipment has a high impedance to ensure no measurement errors are introduced.

5.6 Recommendations

The hybrid anode system installed at Kyle of Tongue bridge appears to be functioning well and the monitoring results over a period of 2 years suggests that any corrosion activity has been controlled effectively by the galvanic phase of the anodes. Based on the results of the data obtained there are no further recommendations for the system installed at Kyle of Tongue.

Table 1 - Steel depolarisation results, Kyle of Tongue Bridge

12/01/2012

Box No	Current ON			Current OFF - 24hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	6.38	-	-460	0	0	-441	-	19
2	7.4	-	-332	0	0	-309	-	23
3	11.7	-	-348	0	0	-297	-	51
4	2.44	-	-369	0	0	-363	-	6

09/08/2012

Box No	Current ON			Current OFF - 48hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	3.84	5.18	-396	0	0	-385	-	11
2	4.38	4.19	-313	0	0	-300	-	13
3	2.55	8.67	-307	0	0	-297	-	10
4	2.88	2.48	-352	0	0	-344	-	8

11/02/2013

Box No	Current ON			Current OFF - 2hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	1.9	1.5	-349	0	0	-340	-775	9
2	1.5	1.5	-276	0	0	-271	-740	5
3	0.3	2.1	-259	0	0	-258	-429	1
4	2.6	0.7	-325	0	0	-323	-655	2

11/03/2013

Box No	Current ON			Current OFF - 2hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	1.6	1.3	-344	0	0	-334	-778	10
2	1.3	1.3	-270	0	0	-264.8	-763	5.2
3	0.2	1.7	-255	0	0	-252.8	-406.7	2.2
4	2.54	0.7	-331	0	0	-328	-650	3

12/03/2013

Box No	Current ON			Current OFF - 24hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	-	-	-344	0	0	-334	-785	10
2	-	-	-270	0	0	-265	-775	5
3	-	-	-255	0	0	-250.7	-431.5	4.3
4	-	-	-331	0	0	-324.6	-656	6.4

23/09/2013

Box No	Current ON			Current OFF - 2hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	2.8	2.7	-386	0	0	-381	-	5
2	2.5	2.5	-314	0	0	-310	-	4
3	0.5	6.6	-270	0	0	-267	-	3
4	1.4	13.8	-343	0	0	-340	-	3

24/03/2014

Box No	Current ON			Current OFF - 3.5hrs			Anode-Steel seperation (mV)	DE (mV)
	Anode1 (mV)	Anode2 (mV)	Potential (mV)	Anode1 (mV)	Anode2 (mV)	Potential (mV)		
1	1.2	1	-383	0	0	-378	-	5
2	1	1.1	-294	0	0	-291	-	3
3	0.1	3.9	-266	0	0	-265	-	1
4	0.5	4.3	-345	0	0	-343	-	2

NOTES:

All reported potentials vs. Ag/AgCl

A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

Table 2 - Calculated corrosion rates, Kyle of Tongue Bridge

Junction Box 1 (Span 8-9) Area 1.156 m2

Date	01/09/2011	12/01/2012	09/08/2012	11/02/2013	11/03/2013	12/03/2013	23/09/2013	24/03/2014
Time lapsed (days)	0	133	343	529	557	558	753	935
Current (=mV/10) mA		0.638	0.384	0.19	0.16	0.16	0.27	0.12
Voltage ON (mV)		-490	-396	-349	-344	-344	-386	-383
Voltage OFF (mV)		-471	-385	-340	-334	-334	-381	-378
DE		19	11	9	10	10	5	5
Icorr (mA/m2)	**38.9**	**0.74**	**0.78**	**0.47**	**0.36**	**0.36**	**1.22**	**0.54**

Junction Box 2 (Span 9-10) Area 0.60 m2

Date	02/09/2011	12/01/2012	09/08/2012	11/02/2013	11/03/2013	12/03/2013	23/09/2013	24/03/2014
Time lapsed (days)	0	132	342	528	556	557	752	934
Current (=mV/10) mA		0.74	0.418	0.15	0.13	0.13	0.25	0.1
Voltage ON (mV)		-332	-313	-276	-270	-270	-314	-294
Voltage OFF (mV)		-309	-300	-271	-264.8	-265	-310	-291
DE		23	13	5	5.2	5	4	3
Icorr (mA/m2)	**6.03**	**1.20**	**1.22**	**1.15**	**0.96**	**1.00**	**2.40**	**1.28**

Junction Box 3 (Span 12-13) Area 0.852 m2

Date	01/10/2011	12/01/2012	08/08/2012	11/02/2013	11/03/2013	12/03/2013	23/09/2013	24/03/2014
Time lapsed (days)	0	103	313	499	527	528	723	905
Current (=mV/10) mA		1.17	0.255	0.03	0.02	0.02	0.05	0.01
Voltage ON (mV)		-348	-307	-259	-255	-255	-270	-268
Voltage OFF (mV)		-297	-297	-258	-252.8	-250.7	-267	-265
DE		51	10	1	2.2	4.3	3	1
Icorr (mA/m2)	**2.47**	**0.64**	**0.69**	**0.82**	**0.26**	**0.13**	**0.46**	**0.27**

Junction Box 4 (Span 16-17) Area 1.224 m2

Date	21/07/2011	12/01/2012	08/08/2012	11/02/2013	11/03/2013	12/03/2013	23/08/2013	24/03/2014
Time lapsed (days)	0	175	385	571	599	600	795	977
Current (=mV/10) mA		0.244	0.209	0.07	0.254	0.254	0.14	0.05
Voltage ON (mV)		-368	-352	-325	-331	-331	-343	-345
Voltage OFF (mV)		-360	-344	-323	-328	-324.6	-340	-343
DE		8	8	2	3	6.4	3	2
Icorr (mA/m2)	**6.8**	**0.88**	**0.78**	**0.75**	**1.30**	**0.84**	**0.99**	**0.63**

NOTES:

All reported potentials vs. Ag/AgCl

A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

6. WHITEADDER, BERWICK

6.1 Structure Details

The Whiteadder bridge forms part of the B6461 to carry traffic over the Whiteadder Water at Canty, near Paxton. The Whiteadder bridge opened in 1973 and is constructed from four steel girders supported on bearings directly above reinforced concrete piers and carries a single carriageway over the Whiteadder Water. The bridge has five spans ranging from 12.5m to 30m and is approximately 90m in total length. The deck is constructed from reinforced concrete beams spanning horizontally between the four primary steel girders. The location and general elevation view can be seen in Figures 7 and 8 respectively. Prior to repair works in January 2007 the bridge exhibited areas of substantial spalling and delamination due to chloride ingress from the leaking of the deck joints.

Figure 7 - Whiteadder Bridge, Berwick

Figure 8 - North Elevation view of Whiteadder Bridge

6.2 Hybrid Anode Details

Approximately 2,200 DuoGuard™ 500 anodes were installed across the entire face of the four reinforced concrete piers to achieve a design life of 30 years. The anodes were installed at a varied spacing between 400-500mm due to the tapered reinforcement arrangement. Steel densities were found to be 2.05m² and 1.95m² of steel per metre squared of concrete for the bottom and top of the piers respectively. The piers also received additional protection in the form of a waterproof coating as seen in Figure 9. Remote monitoring of the hybrid system is utilised on one of the four reinforced concrete piers and was the preferred option of monitoring due to the site location and access restrictions. The data logging equipment is located in a junction box installed at a high level as shown in Figure 10 and is powered by an adjacent solar panel.

Figure 9 - Waterproof surface coating to all reinforced concrete piers

Figure 10 - Data logging equipment

6.3 Visual Inspection

A visual inspection of the reinforced concrete piers was conducted from ground level on 18th March 2014. The waterproof surface coating made it difficult to conduct a hammer tap survey to identify surface cracking or delaminated areas of concrete; however no visible defects were noted.

The reinforced concrete piers were found to be in generally good condition but with some water ingress defects observed. A significant amount of water and rust staining was noted on the piers however it is believed that this arises from the primary steel girders when water ingress occurs through the deck joints or through a fault in the drainage system. The extent of water and rust staining at high levels of the reinforced concrete piers can be seen in Figure 11. On closer inspection, evidence of corrosion of the steel girders was observed near to the location of all bridge joints suggesting that they are now failing to prevent water and chloride ingress from the above carriageway (Figure 12). The ingress of water and possible chlorides to the reinforced concrete will be significantly reduced by the applied waterproof coating on the piers.

It was observed that the run-off from the waterproof coating is causing some deterioration to the IP65 GRP monitoring box which houses the data logging equipment (Figure 10). It is believed that rust staining may be from deterioration of the galvanised steel fixings that were used in the installation. This could lead to potential damage of the monitoring equipment preventing remote depolarisation readings to be taken. No areas of delamination were identified during the inspection.

Figure 11 - Water and rust staining from steel girders

Figure 12 - Corrosion of steel girders in close proximity of bridge joints

6.4 Review of Record Monitoring Data

Steel potential readings and depolarisation results have been remotely monitored at regular intervals by CPT Ltd on one reinforced concrete pier from 18th April 2007 to 12th March 2015. Six reference cells were installed in an upper and lower zone of the pier and a summary of the depolarisation results and calculated corrosion rates can be seen in Table 3.

Table 3 - Calculated corrosion rates, Whiteadder bridge

Date: 19/04/2007	Upper Zone	Lower Zone
Average on potential (mV)	-383	-377
Monitoring zone current (mA)	6.60	2.61
Average instant off potential (mV)	-376	-369
Average total de-polarisation (24 hours) (mV)	42	44
Cathodic current density (mA/m²)*	3.38	1.27
Corrosion rate (mA/m²)**	1.89	0.67

Date: 27/08/2007	Upper Zone	Lower Zone
Average on potential (mV)	-319	-335
Monitoring zone current (mA)	3.81	0.95
Average instant off potential (mV)	-315	-330
Average total de-polarisation (24 hours) (mV)	20	18
Cathodic current density (mA/m²)*	1.95	0.46
Corrosion rate (mA/m²)**	2.48	0.66

Date: 20/10/2007	Upper Zone	Lower Zone
Average on potential (mV)	-326	-300
Monitoring zone current (mA)	2.12	0.41
Average instant off potential (mV)	-320	-297
Average total de-polarisation (24 hours) (mV)	16	12
Cathodic current density (mA/m²)*	1.09	0.20
Corrosion rate (mA/m²)**	1.74	0.43

Date: 06/03/2008	Upper Zone	Lower Zone
Average on potential (mV)	-327	-297
Monitoring zone current (mA)	1.98	0.27
Average instant off potential (mV)	-323	-294
Average total de-polarisation (24 hours) (mV)	11	7
Cathodic current density (mA/m²)*	1.01	0.13
Corrosion rate (mA/m²)**	2.38	0.49

Date: 23/09/2008	Upper Zone	Lower Zone
Average on potential (mV)	-353	-321
Monitoring zone current (mA)	4.51	1.19
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	24	20
Cathodic current density (mA/m²)*	2.31	0.58
Corrosion rate (mA/m²)**	2.42	0.74

Date: 08/04/2009	Upper Zone	Lower Zone
Average on potential (mV)	-331	-301
Monitoring zone current (mA)	2.24	0.36
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	8	6
Cathodic current density (mA/m²)*	1.15	0.18
Corrosion rate (mA/m²)**	3.73	0.76

Date: 12/05/2009	Upper Zone	Lower Zone
Average on potential (mV)	-328	-300
Monitoring zone current (mA)	1.95	0.30
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	9	8
Cathodic current density (mA/m^2)*	1.00	0.15
Corrosion rate (mA/m^2)**	2.88	0.47

Date: 04/06/2013	Upper Zone	Lower Zone
Average on potential (mV)	-319	-279
Monitoring zone current (mA)	1.25	0.18
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	8	5
Cathodic current density (mA/m^2)*	0.64	0.09
Corrosion rate (mA/m^2)**	2.07	0.45

Date: 20/06/2014	Upper Zone	Lower Zone
Average on potential (mV)	-306	-270
Monitoring zone current (mA)	0.92	0.18
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	5	5
Cathodic current density (mA/m^2)*	0.47	0.09
Corrosion rate (mA/m^2)**	2.47	0.46

Date: 20/06/2014	Upper Zone	Lower Zone
Average on potential (mV)	-306	-270
Monitoring zone current (mA)	0.92	0.18
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	5	5
Cathodic current density (mA/m^2)*	0.47	0.09
Corrosion rate (mA/m^2)**	2.47	0.46

Date: 12/03/2015	Upper Zone	Lower Zone
Average on potential (mV)	-302	-268
Monitoring zone current (mA)	0.48	0.08
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	4	4
Cathodic current density (mA/m^2)*	0.25	0.04
Corrosion rate (mA/m^2)**	1.60	0.24

NOTES:

All reported potentials vs. $Cu/CuSO_4$

Calculated area protected by monitoring zone $0.7m^2$

*Based on an approximate steel density of $1.95m^2$ and $2.05m^2$ per m^2 of concrete for upper and lower zones

**A corrosion rate of less than $2mA/m^2$ signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

6.5 Corrosion Risk Assessment

The steel depolarisation readings and calculated corrosion rates shown in Table 3 suggest that the hybrid anode system installed at Whiteadder Bridge is performing satisfactorily. In some cases for the upper zone the calculated corrosion rate increases above the $2mA/m^2$ recommended value for passive steel however over time it can be seen that this value fluctuates depending on the average depolarisation observed across six monitoring zones. The depolarisation data taken on 12th March 2015 show that the hybrid anodes have reduced the corrosion rate to $1.60mA/m^2$ indicating passive steel, 8 years after installation. This information coupled with the increase in steel 'on potential' values over time for both zones highlights adequate performance of the system.

The ingress of water and possible chlorides to the reinforced concrete will be significantly reduced by the applied waterproof coating at Whiteadder Bridge, which in turn reduces the risk of corrosion initiation in the reinforced concrete piers.

6.6 Recommendations

The hybrid anode system installed at Whiteadder Bridge appears to be performing adequately. It is recommended that care is taken to install monitoring enclosures away from possible sources of water ingress such as surface water run-off.

7. LAVEROCK HALL, NEWCASTLE

7.1 Structure Details

Laverock Hall overbridge forms part of the A189 carrying traffic over the A1061. The Laverock Hall overbridge was constructed in two halves for the Northbound and Southbound carriageways. The two 43 metre long bridges have four-spans and are constructed from simply supported pre-stressed beams spanning between 3 reinforced concrete crosshead beams and supporting columns. Two reinforced concrete abutments are located at each end of the structure. The bridge deck is constructed from a concrete infill between the pre-stressed beams. The location and general elevation view can be seen in Figures 13 and 14 respectively. Prior to repair works in March 2006 the bridge exhibited areas of substantial spalling and delamination due to chloride ingress from the leaking of the deck joints.

Figure 13 - Laverock Hall overbridge

Figure 14 - Elevation view of Laverock Hall overbridge (looking Eastbound)

7.2 Hybrid Anode Details

Concrete repairs were made to areas of significant corrosion damage. DuoGuard™ 500 anodes were installed at 400-500mm spacings in the reinforced concrete abutments and piers where significant levels of chloride content were found. The design life of the system was 30 years and was based on steel densities of 4.09m² and 1.17m² per metre squared of concrete for the pier beams and columns respectively. Reference electrodes and data logging equipment were installed on the bridge to allow remote monitoring of the structure. The reinforced concrete abutments and piers had an additional waterproof coating applied. It should be noted that the waterproof coating was only applied to one sixth of the South abutment (Figure 15).

Figure 15 - Waterproof coating to South abutment

7.3 Visual Inspection

A visual inspection of the reinforced concrete piers was conducted from ground level on 18th March 2014. The waterproof surface coating made it difficult to effectively conduct a hammer tap survey to identify surface cracking or delaminated areas of concrete; however, no visible defects were noted. The reinforced concrete piers were found to be in generally good condition with only minor defects observed. Water staining was observed at high level in the reinforced concrete piers which suggests that bridge joints are leaking from the above carriageway (Figure 16).

Figure 16 - Water staining on reinforced concrete pier

The enclosure for the data logging equipment was found to be in good condition (Figure 17). Minor cracking was observed in the waterproof coating in a number of locations; however the depth of the crack could not be confirmed. Only one defect which was outside the area of influence of the hybrid CP system was identified during the hammer tap survey covering an area of approximately 1000 x 400mm. It is a possibility that the defect may be due to a de-bonding of the waterproof coating as other minor surface coating defects were also observed during the inspection (Figure 18). Alternatively it may be due to delamination of the concrete surface as there is a small possibility that the adjacent anode zone has been disconnected.

Figure 17 - Monitoring equipment and steel conduit, South pier, verge facing

Figure 18 - Surface coating defect

7.4 Review of Record Monitoring Data

Steel potential readings and depolarisation results have been remotely monitored at regular intervals by CPT Ltd from 27th August 2007 to 11th March 2015. Reference electrodes were installed at ten locations along the pier beams and two locations on the pier columns. A summary of the depolarisation results and calculated corrosion rates can be seen in Table 4.

Table 4 - Calculated corrosion rates, Laverock Hall Bridge

Date: 27/08/2007	Pier Beam	Pier Column
Average on potential (mV)	-337	-279
Monitoring zone current (mA)	1.40	1.19
Average instant off potential (mV)	-329	-257
Average total de-polarisation (24 hours) (mV)	15	48
Cathodic current density (mA/m²)*	0.34	1.02
Corrosion rate (mA/m²)**	0.59	0.48

Date: 20/10/2007	Pier Beam	Pier Column
Average on potential (mV)	-324	-273
Monitoring zone current (mA)	0.85	0.82
Average instant off potential (mV)	-317	-253
Average total de-polarisation (24 hours) (mV)	15	44
Cathodic current density (mA/m²)*	0.21	0.70
Corrosion rate (mA/m²)**	0.36	0.37

Date: 06/03/2008	Pier Beam	Pier Column
Average on potential (mV)	-318	-268
Monitoring zone current (mA)	0.74	0.75
Average instant off potential (mV)	-312	-256
Average total de-polarisation (24 hours) (mV)	15	43
Cathodic current density (mA/m²)*	0.18	0.64
Corrosion rate (mA/m²)**	0.31	0.35

Date: 23/09/2008	Pier Beam	Pier Column
Average on potential (mV)	-257	-211
Monitoring zone current (mA)	0.42	1.93
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	34	12
Cathodic current density (mA/m²)*	0.10	1.65
Corrosion rate (mA/m²)**	0.07	3.55

Date: 12/05/2009	Pier Beam	Pier Column
Average on potential (mV)	-221	-201
Monitoring zone current (mA)	0.03	0.20
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	4	2
Cathodic current density (mA/m²)*	0.01	0.17
Corrosion rate (mA/m²)**	0.05	2.18

Date: 20/06/2014	Pier Beam	Pier Column
Average on potential (mV)	-254	-197
Monitoring zone current (mA)	0.01	0.06
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	1	2
Cathodic current density (mA/m²)*	0.00	0.05
Corrosion rate (mA/m²)**	0.09	0.71

Date: 11/03/2015	Pier Beam	Pier Column
Average on potential (mV)	-233	-192
Monitoring zone current (mA)	0.01	0.07
Average instant off potential (mV)	-	-
Average total de-polarisation (24 hours) (mV)	1	1
Cathodic current density (mA/m²)*	0.00	0.06
Corrosion rate (mA/m²)**	0.09	1.58

NOTES:

All reported potentials vs. $Cu/CuSO_4$

Calculated area protected by monitoring zone 0.7m²

*Based on an approximate steel density of 4.09m² and 1.17m² per m² of concrete for pier beams and columns respectively

**A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

7.5 Corrosion Risk Assessment

The steel depolarisation readings and calculated corrosion rates shown in Table 4 suggest that the hybrid anode system installed at Laverock Hall Bridge is performing satisfactorily, 8 years after installation. In most cases the calculated corrosion rates remain below the 2mA/m² recommended value for passive steel. On 23rd September 2008 and 12th May 2009, a higher corrosion rate was measured in the pier column at 3.55mA/m² and 2.18mA/m² respectively. Recent measurements have shown that this value has reduced back below the 2mA/m² threshold indicating that the hybrid anodes have effectively reduced the corrosion risk. Table 4 also shows that the steel 'on potential' values increase over time for both the beam and column zones highlighting adequate performance of the system.

CPT Ltd have continued to record long term monitoring data, taking an 'on potential' and current reading at daily intervals from 28th July 2006 to 10th March 2015. Figure 19 shows how the steel potentials have continued to shift towards more passive conditions over time. This data combined with the recorded depolarisation readings and the visual inspection suggests a low corrosion risk for this structure.

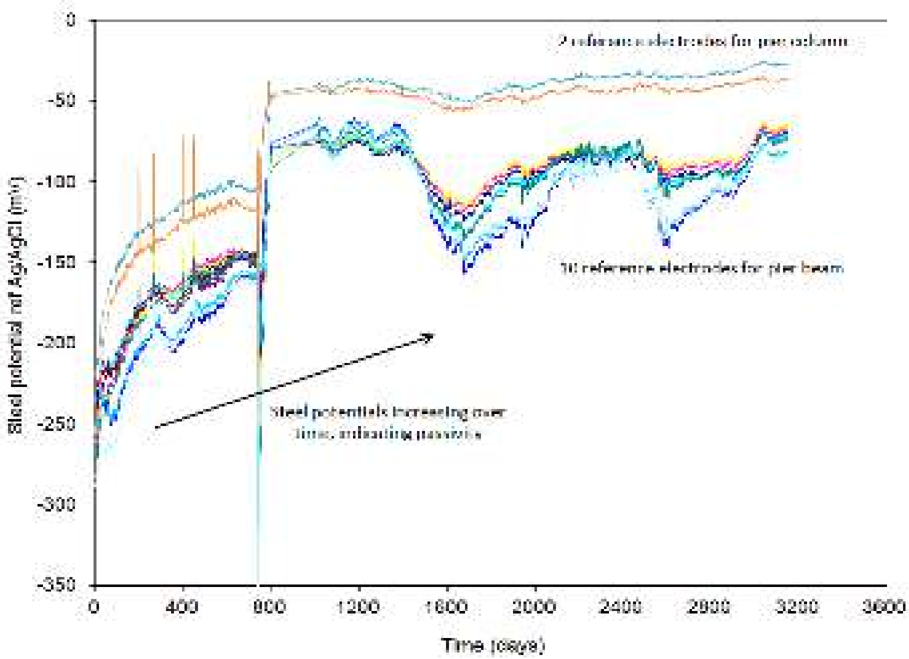

Figure 19 - Steel potential shift with time, Laverock Hall Bridge

7.6 Recommendations

The data recorded at Laverock Hall indicates passive steel conditions and suggests a low risk of corrosion to the structure. It is recommended to increase redundancy in the design where possible using titanium terminated copper cables. This has an additional benefit of reducing voltage drops between the power supply and hybrid anode zone.

8. STORTH LANE, SOUTH NORMANTON

8.1 Structure Details

The Storth Lane bridge carries the A38 dual carriageway over Storth Lane and is located in close proximity to where the A38 joins the M1 motorway. The structure belongs to the Highways Agency however is managed and maintained by the owning agent, AMScott. The single span structure is constructed from simply supported pre-stressed beams spanning between the two reinforced concrete abutments. The bridge deck is constructed from a concrete infill between the pre-stressed beams. Expansion joints exist above the abutments to allow sufficient movement in the bridge deck. The location plan and elevation view of Storth Lane bridge are shown in Figures 20 and 21 respectively. Hybrid anodes were installed along a single row at high level in the bridge abutments in 2007 to prevent further corrosion damage from the leaking bridge joints. No major repair works were conducted on this bridge.

Figure 20 - Storth Lane Bridge

Figure 21 - Elevation view of Storth Lane Bridge (looking Eastbound)

8.2 Hybrid Anode Details

DuoGuard™ 500 anodes were installed in a single row along the length of the South abutment only, approximately 400mm below the bearing shelf at 420mm horizontal spacings to achieve a design life of 25 years. The calculated steel density is 1.0m² per metre squared of concrete. A departure from standard (ID: 49865) was issued for the installation of the hybrid system. The anodes are separated into eight individual zones, four of which are for monitoring purposes where reference electrodes have been installed along the North Abutment only. Remote monitoring is not available at this site and readings have to be taken from the monitoring enclosure itself. No major repair works were carried out on the reinforced concrete abutments at the time of anode installation.

8.3 Visual Inspection

A visual inspection of the reinforced concrete abutments was conducted from ground level on 23rd May 2014. On the day of inspection it was noted that significantly more water ingress was observed on the South abutment compared to the North abutment (Figures 22 and 23 respectively).

Figure 22 - Storth Lane South abutment (North facing)

Figure 23 - Storth Lane North abutment (South facing)

Large areas of surface delamination and honeycombing were observed along the South abutment (2-3mm deep) as seen in Figure 24. These areas are located at low levels of the abutment well away from the hybrid treated section, in conjunction with areas of water ingress from the leaking bridge joints and also within the spray zone from the adjacent single carriageway. A significant amount of cracks were also observed on both abutments and ranged from 1m to 2.5m in length and were 1 to 2mm in width. The cracks are located at similar locations on both abutments which suggest that the cracks may be due to drying shrinkage of the concrete rather than corrosion damage. Figure 25 shows cracking to the North abutment.

Rust and water staining from the bridge joint was observed at the South West corner of the South abutment (Figure 26). As the visual inspection was only conducted from ground level the source of the rust staining could not be confirmed. The area surrounding the hybrid anode installation showed no signs of corrosion induced deterioration.

Figure 24 - Honeycombing and surface delamination to South abutment

Figure 25 - Shrinkage cracking to North abutment

Figure 26 - Rust and water staining from bridge joint on South abutment

8.4 Review of Monitoring Data

Steel potential readings and depolarisation readings were taken initially by AECOM and CPT Ltd. on 23rd May 2014. A summary of the depolarisation results and calculated corrosion rates can be seen in Table 5. Channels refer to individual zones, with zones 2, 4, 6 and 8 representing monitoring locations.

Table 5 - Depolarisation readings and corrosion rates of Storth Lane Bridge, North abutment

Location: Storth Lane, South Normanton, Derbyshire **Date Inspected:** 23/05/2014 **Conditions:** Dry, Sunny, Humid **Temperature:** ~19°C **Structure:** Some visible wetting of abutment walls from failed bridge joints. Overall relatively dry.	North Abutment - Anodes installed in a single row below the bearings of the abutment and seperated into four individual zones. A monitoring location is available for each anode zone therefore 8 channels in total.							
Channel*	1	2	3	4	5	6	7	8
On potential (mV)	-	-442	-	-344	-	-466	-	-472
Zone current (mA)	0.39	0.22	0.00	0.03	5.01	0.53	2.51	0.30
Anode driving voltage (mV)	-	223	-	381	-	272	-	191
Instant off potential (mV)	-	-441	-	-343	-	-465	-	-470
Off potential (20 mins) (mV)	-	-437	-	-343	-	-450	-	-469
Off potential (1 hour) (mV)	-	-436	-	-343	-	-450	-	-468
Total de-polarisation (mV)	-	6	-	1	-	16	-	4
Cathodic current density (mA/m²)**	-	0.22	-	0.03	-	0.53	-	0.30
Corrosion rate (mA/m²)***	-	0.95	-	0.78	-	0.85	-	1.95

NOTES:

All reported potentials vs. $Cu/CuSO_4$

*Channels 1, 3, 5 and 7 anode zones only. Channels 2, 4, 6 and 8 monitoring zones only

**Based on a calculated steel density of 1.0m² per m³ of concrete

***A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

The data in Table 5 shows a relatively low magnitude of depolarisation after a time of one hour. The majority of depolarisation is achieved within the first 20 minutes of disconnecting the system and the magnitude is larger when the current output of the anodes are significantly higher. The calculated corrosion rates are all below 2mA/m².

8.5 Corrosion Risk Assessment

The steel depolarisation readings and calculated corrosion rates, shown in Table 5 suggest that the hybrid anode system installed at Storth Lane bridge is performing satisfactorily. The relatively low magnitude of depolarisation suggests that corrosion activity is minimal and it is possible that the reinforcing steel is now in a benign environment indicated by the low depolarisation results seen in 3 out of 4 monitoring locations. There is further evidence for this in the fact that the majority of depolarisation was achieved within the first 20 minutes of disconnecting the anode system. All corrosion rates calculated also indicate passive conditions. The higher anode current output observed on channel 6 may be due to localised wetting of the zone (Figure 26).

8.6 Recommendations

Reference electrodes have only been installed within the North abutment of Storth Lane Bridge which appears to be a drier and more benign environment compared to the South abutment which showed signs of further deterioration at low levels and water run-off from the expansion joints. Therefore collection of monitoring data from both abutments would have enabled a stronger conclusion to be made on the effectiveness of the hybrid anode system installed at Storth Lane. It is understood that the installation of monitoring locations does increase the cost of refurbishment and it is down to client discretion whether long term monitoring is a necessity.

9. PASTON INTERCHANGE, PETERBOROUGH

9.1 Structure Details

The A47 Paston Interchange in Peterborough is a dual carriageway intersecting the A15 with a flyover roundabout at Junction 20. The two 41 metre long bridges support a dual carriageway roundabout above the A15. The four-span bridge consists of 27 simply supported pre-stressed beams spanning between 3 reinforced concrete crosshead beams and supporting columns. The reinforced concrete abutments at both ends of each structure are further supported by pulverised fuel ash infill embankments. The bridge deck is constructed from a concrete infill between the pre-stressed beams. The structure is fixed above the intermediate pier column and free to move above the outer columns. Expansion joints exist above the outer columns and abutments to allow sufficient movement in the bridge deck.

The location and general elevation view can be seen in Figures 27 and 29 respectively. Hybrid anodes have been installed on the four verge piers on both main faces (traffic and verge). However, inspection of the piers within the central reservations were not part of this project and were found to be in good condition.

Figure 27 - A47 Paston Interchange

Figure 28 - Elevation view of North East and North West piers (looking Northbound)

9.2 Hybrid Anode Details

The hybrid system was installed on the outer piers of both bridge structures to prevent further corrosion damage and the piers are identified as North-East, South-East, North-West and South-West (Figure 29). Hybrid anodes have been installed on both the traffic and verge face of these outer piers. The specification for a 25 year design life led to the implementation of DuoGuard™ 350 hybrid anodes spaced at 384mm horizontally and 500mm vertically in a staggered grid formation. Each pier face is separated into 8 zones which are individually wired back to a junction box installed at one end of the pier (Figure 29). Five steel connections are made in between zones to ensure steel continuity across the structure and two Manganese/Manganese Dioxide (Mn/MnO_2) references cells are installed on each face to allow monitoring of steel and anode potentials. The two cable termination enclosures (junction boxes) located on the side of the abutment and the arrangement of the terminal blocks located inside the enclosures are shown in Figures 30 and 31 respectively. There are approximately 6 hybrid anodes installed per square meter and the steel density of each pier is approximately 0.84m² per metre squared of concrete.

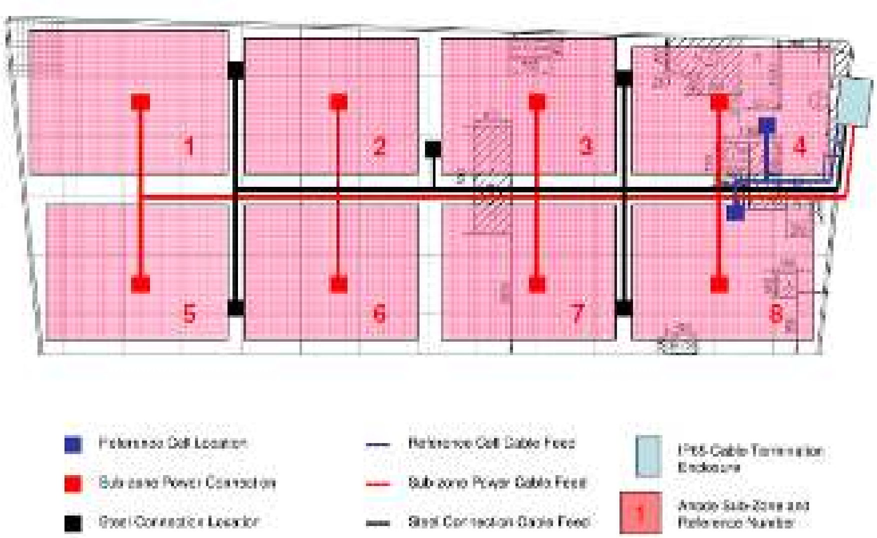

Figure 29 - Arrangement of hybrid anode zones, steel connections and reference cell locations

Figure 30 - Junction boxes located on the end of abutments

Figure 31 - Arrangement of terminal block

9.3 Visual Inspection

A visual inspection of the structure was conducted from ground level and covered both the traffic and verge faces of all four piers. Overall, there were little or no signs of corrosion found and only a small number of defects were visible. The areas of steel reinforcement, originally identified with a low concrete cover, were re-constructed to provide an adequate cover depth (Figure 32). During the inspection a superficial defect was identified adjacent to a patch repair.

Figure 32 - Low cover areas reinstated to an adequate depth

A number of longitudinal cracks outside the zone of influence of the hybrid CP system, approximately 1-2mm wide, were observed in the lower section of the piers. It was noted that these cracks were not specified as part of the repair works as a potential mapping survey indicated little risk of corrosion (Figure 33). It was evident from the visual inspection that the majority of bridge joints were in a poor condition (Figure 34) which is causing a significant amount of water ingress from the carriageway above (Figure 35). It is assumed that this water could contain chlorides from de-icing salts which could significantly increase the risk of chloride-induced corrosion.

Figure 33 - Longitudinal cracking

Figure 34 - Deterioration of bridge joints above abutment walls

Figure 35 - Evidence of water ingress (North-West abutment, verge face)

9.4 Review of Monitoring Data

Monitoring was previously undertaken at 13, 26 and 39 weeks following the installation of the hybrid corrosion protection anodes (Report numbers: CPT240413A; CPT230713A and CPT221013A respectively). In all three reports, it was noted that potential readings and corrosion rates taken represented passive steel conditions after a 4 hour depolarisation period and also showed that the hybrid anodes were functioning as expected in the galvanic phase. In some cases, at 39 weeks, the depolarised potentials became more negative which may suggest the onset of corrosion activity. However, these areas however coincided with visible water ingress from the failing bridge joints which suggests that the depressed potentials are a result of the increase in moisture. Steel potential readings and depolarisation readings were taken jointly by AECOM and CPT Ltd. after 52 weeks on 9th and 10th January 2014. A summary of the data is shown in Table 6.

The 52-week monitoring data shows depolarisation readings ranging from 6mV to 106mV over a 24 hour period. The changes in depolarisation across the 4 piers correlates well to the extent of water ingress observed during the visual inspection. All calculated corrosion rates are less than $2mA/m^2$.

Table 6 - 52 Week monitoring data for Paston Interchange

Location: Paston Interchange, Peterborough **Date Inspected:** 09/01/2014 - 10/01/2014 **Conditions:** Dry, Sunny **Temperature:** ~7°C **Structure:** Some wetting of pier walls from failed bridge joints. Drier than readings taken at 30 weeks	North West Pier				South West Pier				North East Pier				South East Pier			
	Traffic Face		Verge Face		Traffic Face		Verge Face		Traffic Face		Verge Face		Traffic Face		Verge Face	
	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
Reference electrode location (anode zone no.*)	5	7	5	7	1	8	2	8	8	4	3	8	5	1	1	1
On potential (mV)	-365	-400	-309	-418	-410	-386	-375	-384	-363	-346	-292	-269	-356	-225	-332	-279
Monitoring zone current (mA)	0.12	0.54	0.01	2.67	0.73	0.91	1.03	0.11	0.88	0.46	0.04	1.12	0.07	0.01	0.04	0.19
Remaining anodes current (mA)	34.4		25.0		31.2		42.7		19.6		17.9		3.3		4.3	
Instant off potential (mV)	-365	-400	-308	-418	-408	-384	-374	-383	-361	-346	-291	-269	-356	-225	-332	-279
Depolarised steel potential (mV)	-367	-343	-302	-327	-302	-317	-335	-337	-287	-317	-274	-262	-347	-216	-322	-264
Total de-polarisation (mV)	18	57	6	91	106	67	39	46	74	29	17	7	8	9	10	15
Total de-polarisation time (Hours)	26.0		26.4		25.8		25.2		23.8		24.4		24.2		24.9	
Cathodic current density (mA/m²)**	0.56	0.56	0.40	1.40	0.50	0.50	0.69	0.69	0.32	0.32	0.29	0.29	0.06	0.06	0.08	0.08
Corrosion rate (mA/m²)***	0.19	0.21	1.73	1.07	0.07	0.15	0.42	0.34	0.08	0.27	0.44	1.08	0.19	0.17	0.21	0.14

NOTES:

All reported potentials vs. $Cu/CuSO_4$

Calculated area protected by monitoring zone 0.7m²

*Zones 1-4 upper row, 5-8 lower row

**Based on a calculated steel density of 0.84m² per m³ of concrete

***A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

9.5 Corrosion Risk Assessment

As stated above, the recorded depolarisation readings correlate well to the extent of water ingress from the failing bridge joints. Areas of wet concrete, as a result of water leaking through the expansion joints, will result in lower concrete resistivity which will increase the current demand. In addition, leaking water may be carrying chlorides, which will result in a change of environmental conditions and as such increase current output by the hybrid anodes.

All corrosion rates calculated from the depolarisation results indicate passive conditions at the surface of the reinforcing steel therefore the hybrid anode system appears to be performing satisfactorily and is achieving the criteria set out in ISO 12696:2012. The visual inspection indicated little or no defects that have occurred since the repair works were carried out. This data, combined with previous reports, indicates passive reinforcing steel conditions have been maintained throughout the first year of system operation. This allows a strong conclusion to be made that the hybrid anode system is working effectively. The highest corrosion rate observed of 1.73mA/m² was located in Zone 1 of the verge face of the North West pier. The higher corrosion rate may be due to a localised area of water ingress within the monitoring zone; however is still considered to be a low risk of corrosion.

9.6 Recommendations

The hybrid anode system installed at the A47 Paston Interchange appears to be functioning satisfactorily and the monitoring results over a period of 52 weeks suggests that the reinforcement remains in passive condition. Based on the results of the data obtained there are no further recommendations for the system installed at Paston Interchange.

It would be beneficial to continue to obtain long-term monitoring data in accordance with ISO 12696:2012 to assess the continued performance of the system.

10. M69 JUNCTION 2, HUNCOTE, LEICESTER

10.1 Structure Details

The Junction 2 and Huncote bridge abutments are situated on the M69 motorway in Leicestershire. The two structures consist of simply supported pre-stressed beams spanning between the North and South abutments with an intermediate pier crosshead beam and supporting columns. The location of both structures and the general elevation view of Junction 2 can be seen in Figures 36, 37 and 38 respectively. Concrete repairs and hybrid anode installation was conducted following inspection reports which identified corrosion activity and significant chloride levels. The repair works in 2012 were conducted on three abutments along the Westbound carriageway. Areas of spalling and delamination were evident from steel reinforcement corrosion in the abutments. No repairs were made to the intermediate pier columns of the structures.

Figure 36 - M69 Junction 2 Bridge abutments, Westbound carriageway

Figure 37 - M69 Hunctote Bridge abutment, Westbound carriageway between J1 and J2

Figure 38 - Elevation view of M69 Junction 2 Bridge, looking North

10.2 Hybrid Anode Details

DuoGuard™ 750 anodes were installed in a single row at 350mm centres along the length of all three abutments 200mm below the bearing shelf to achieve a design life of 25 years. The steel density in the abutments was 0.75m² per metre squared of concrete. The anodes are separated into two individual zones per abutment and wired back to a centrally mounted junction box. Each zone contains a reference electrode location to enable long term monitoring of the structure. Figure 39 and 40 show the wiring schematic for the hybrid anode installation and the arrangement of connections within the terminal block respectively.

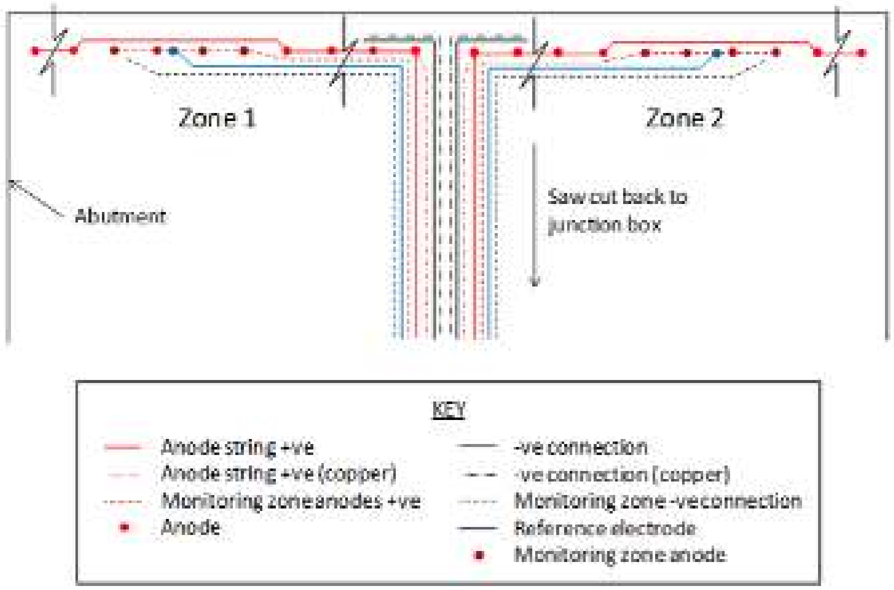

Figure 39 - Wiring schematic for M69 abutments Hybrid anode installation

Figure 40 - Arrangement of terminal block connections

An additional waterproof coating was applied to the surfaces of the abutments upon completion of all repair works to prevent further ingress of water and chloride ions.

10.3 Visual Inspection

A visual inspection of the structure was conducted from ground level on 23rd May 2014 and covered the three abutments with the hybrid anode system installed. There were little or no signs of corrosion found and only a small number of defects were visible. The abutment at Huncote Bridge only showed minor signs of water ingress to the East side from the above carriageway probably as a result of degradation of the expansion joints (Figure 41).

Figure 41 - Water ingress on Huncote Bridge abutment (East side)

The two abutments at Junction 2 of the M69 motorway exhibited a similar extent of water ingress and staining (Figure 42). This again was more prominent at the top of the abutments which suggests water ingress through failing bridge joints from the above carriageway. Surface defects (honeycombing) and localised hairline cracking recorded at lower levels away from the hybrid anode installation (Figure 43). It is unclear whether these cracks have occurred since the hybrid anode installation or whether these areas were missed as part of the concrete repair works in 2012. The cracks ranged from 500mm to 1.2m in length and were only observed in two locations across both abutments at Junction 2. The crack widths were not measured.

Figure 42 - Water ingress at Junction 2 abutment

Figure 43 - Surface defects (honeycombing) to abutment at Junction 2

10.4 Review of Monitoring Data

Steel potential readings and depolarisation readings were taken jointly by AECOM and CPT Ltd on 23rd May 2014. Due to works access restrictions along the M69 motorway no depolarisation data was recorded therefore a corrosion rate cannot be calculated. A summary of the recorded potentials and currents can be seen in Table 7. Abutments 1 to 3 are numbered from West to East. Therefore abutments 1 and 2 are located at Junction 2 and abutment 3 is located at Huncote Bridge.

Table 7 - Depolarisation and calculated corrosion rates for M69 Junction 2 and Huncote Bridge abutments

Location: M69 Motorway, Junction 2 and Huncote Bridge, Leicestershire **Date inspected:** 23/05/2014 **Conditions:** Dry, Sunny **Temperature:** ~15°C **Structure:** Some wetting of pier walls from failed bridge joints. Minor defects noted	**Abutment 1 (Junction 2)**		**Abutment 2 (Junction 2)**		**Abutment 3 (Huncote Bridge)**	
	Left Hand Zone	**Right Hand Zone**	**Left Hand Zone**	**Right Hand Zone**	**Left Hand Zone**	**Right Hand Zone**
On potential (mV)	-365	-299	-381	-377	-411	-510
Monitoring zone current (mA)	0.50	0.47	0.45	0.38	1.80	0.20
Remaining anodes current (mA)	0.50	1.60	2.43	0.93	0.66	0.66
Monitoring zone driving voltage (mV)	191	202	222	191	-	-
Anode driving voltage (mV)	223	214	214	177	247	220
Cathodic current density (mA/m²)*	0.67	0.63	0.61	0.48	2.40	0.27

NOTES:

All recorded potentials vs. Cu/CuSO4

Calculated area protected by monitoring zone 0.7m²

*Based on a calculated steel density of 0.75m² per m² of concrete

**A corrosion rate of less than 2mA/m² signifies passive steel (BS EN ISO12696:2012) with a loss of less than 2µm/year

The data in Table 7 shows that the hybrid anode system is operational at these sites. Full depolarisation data would not be possible at this site without appropriate traffic management in place.

10.5 Corrosion Risk Assessment

The corrosion rates of the steel reinforcement in the abutments cannot be calculated without sufficient depolarisation data available. Therefore a true corrosion risk assessment cannot be conducted at this site. The data collected does show that the monitored anode zones are effectively distributing a protective current to the steel. This observation combined with the small number of defects noted in the visual inspection of the site indicate that the hybrid anodes are performing satisfactorily however an extended depolarisation test would be required to clarify this assumption.

10.6 Recommendations

There is little evidence of corrosion or defects on the M69 Junction 2 and Huncote abutments. Due to access restrictions to collect data, the results of the corrosion assessment is inconclusive and further testing, by means of extended depolarisation is recommended to establish whether the system is performing satisfactorily.

11. CONCLUSIONS

AECOM were commissioned by Concrete Preservation Technologies (CPT) Ltd. to undertake an independent appraisal of the site performance of DuoGuard™ Hybrid Anode™ systems installed on 6 bridge structures located throughout the UK. After a review of the recorded monitoring data and site visual inspections the following overall conclusions can be made:

- The six structures were generally found to be in good condition following recent refurbishment works.
- The areas of reinforced concrete protected by the hybrid anode technology were found to have no defects associated.
- The results of a depolarisation test suggest that the hybrid anodes are protecting effectively the reinforcement which is considered to be in passive condition.
- In many cases the depolarisation readings were found to be much lower than the standard 100mV criteria set out in ISO 12696:2012. However the calculated corrosion rates were mostly below the threshold of $2mA/m^2$ suggested by ISO 12696:2012, for passive reinforcement.
- Low magnitude depolarisation readings were found to coincide with areas of benign and dry environments where there is little risk of corrosion at present.

In most cases there were no further recommendations for installation of the hybrid anode systems as they appear to be working satisfactorily with minimal defects noted upon inspection. Site specific and general recommendations have been made on other aspects of the design which should be considered when designing new systems. These are detailed below:

Whiteadder, Berwick

- It is recommended that care is taken to install monitoring enclosures away from possible sources of water ingress such as surface run-off and have a suitable IP rating for the environment they are exposed to. This may be more applicable when waterproof coatings have been applied.

Laverock Hall, Newcastle

- It is recommended to increase redundancy in the system, titanium terminated copper cables can be connected to each zone. This has an additional benefit of reducing voltage drops between the power supply and hybrid anodes.

Storth Lane, South Normanton

- It was observed that reference electrodes were only installed within the North abutment of the structure which appears to be a drier, more benign environment compared to the South abutment which showed signs of further deterioration, at lower levels, away from the hybrid anode installation.
- It is recommended that monitoring equipment be installed to areas which represent the highest corrosion risk.

Paston Interchange, Peterborough

- It would be beneficial to continue to obtain long-term monitoring data in accordance with ISO 12696:2012 to assess the continued performance of the system. For sites with difficult access conditions it may be required to facilitate remote monitoring.

M69, Junction 2

- It is recommended that an extended depolarisation test is conducted on these abutments to establish that the system is performing satisfactorily from calculated corrosion rates.