KOEBERG NUCLEAR POWER STATION

LONG TERM REPAIR STRATEGIES FOR THE CONTAINMENT BUILDINGS - EXPERT PANEL REPORT

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ABSTRACT

The containment buildings at Koeberg Nuclear Power Station have developed significant reinforcement corrosion damage with widespread delamination. In response to this situation, Eskom appointed an international Expert Panel to advise on suitable repair strategies for service life extension for the containment buildings.

A workshop of the expert panel was held in Cape Town during the week of 03 – 07 November 2014. During the workshop the Panel performed a site visit at KNPS, met with Eskom representatives to discuss project requirements and developed a suitable repair system solution which would protect the containment structures over the extended life of the power station, calculated to be 40 years from 2015.

It was concluded that:

- The containment structures are at a very advanced state of reinforcement corrosion damage and future reinforcement corrosion damage in presently unrepaired areas is expected to develop exponentially with time and result in more widespread delamination.
- The end of the operational service life of the containment structures may be reached soon if future corrosion damage is not prevented through the application of a long-term repair solution.
- The presently specified patch repair methodology follows state-of-the-art procedures and good practice for localised zones of degradation but will not provide protection to the overall containment structures for the required remaining service life of 40 years.
- The only available repair method identified which can meet the defined performance criteria for the containment structures is cathodic protection using impressed current. Design and implementation of a CP system for such important structures should only be undertaken by internationally qualified companies.
- Routine monitoring and periodical testing of the cathodic protection system must be carried out. Maintenance and possible replacement of the system over the extended lifespan will be required.
- The repair strategies developed for the containment structures may or may not be suitable for other structures at KNPS. Suitable repair strategies should be developed for each individual structure based on individual condition assessments and performance requirements.

It is strongly recommended that a long term protection system, in the form of impressed current cathodic protection, be implemented on both containment structures immediately after completion of local repairs.

CONFIGURATION CONTROL

Document History

Rev.	Date	Preparer	Changes
A	2014-11-20	Prof. H. Beushausen	New Document
B	2014-12-19	Prof. H. Beushausen	Reviewer’s Comments incorporated into report
0	2015-01-08	Prof. H. Beushausen	Issued to Client

Document Approval

Action	Designate	Organisation	Signature
Prepared	Prof. H. Beushausen	UCT	
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Document Retention Time

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Controlled Disclosure

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ABBREVIATIONS

This list contains the abbreviations used in this document.

Abbreviation or Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
AWS	American Welding Society
CA	Control of Anodic Areas
CC	Cathodic Control
CP	Cathodic Protection
CR	Concrete Restoration
EPRI	Electric Power Research Institute
FRP	Fibre Reinforced Polymer
HCP	Half-Cell Potential
ICRI	International Concrete Repair Institute
ILRT	Integrated Leak Rate Test
INSA	Institut National des Sciences Appliquées
KNPS	Koeberg Nuclear Power Station
MCI	Migrating Corrosion Inhibitors
NACE	*formerly known as* 'National Association of Corrosion Engineers'
NSE	Nuclear Structural Engineering (Pty) Ltd
PReq	Performance requirements
PT	Post-Tensioned
RP	Restoring Passivity
TNO	Netherlands Organisation for Applied Scientific Research

1. INTRODUCTION

1.1 PROJECT BACKGROUND AND EXPERT PANEL COMPOSITION

The containment buildings at Koeberg Nuclear Power Station (KNPS) in the Western Cape Province, South Africa, have developed significant reinforcement corrosion damage with widespread delamination. In response to this situation, Eskom appointed an international Expert Panel to advise on suitable repair strategies for service life extension for the containment buildings.

The Expert Panel consists of the following individuals:

- Associate Professor Hans Beushausen, University of Cape Town, South Africa
- Professor Rob Polder, Delft Technical University and TNO (Netherlands Organisation for Applied Scientific Research), the Netherlands
- Professor Mohamad Nagi, American University, Dubai
- Professor Raoul Francois, Institut National des Sciences Appliquées de Toulouse, France
- Dr. Maria Guimaraes, Electric Power Research Institute (EPRI), USA
- Samuel Johnson, Electric Power Research Institute (EPRI), USA

A workshop was held in Cape Town during the week of 03 – 07 November, attended by all Expert Panel members. During the workshop the Panel performed a site visit at KNPS, met with Eskom representatives to discuss project requirements, and developed suitable repair system solutions for the containment structures. All of the meetings during the workshop were attended by Eskom and NSE representatives. A list of attendees of the meetings is provided in 0 List of attendees at the workshop meetings.

In addition to the development of long-term repair and maintenance measures, the Expert Panel was asked to comment on the recently performed condition assessment and the specified patch repair method.

1.2 OBJECTIVE

This report presents a summary of the workshop discussions and consolidates the opinions expressed by the Panel members for a long term repair strategy for the containment buildings.

1.3 SCOPE AND LIMITATIONS

The work of the Expert Panel was limited to the following scope:

- Chloride-induced reinforcement corrosion damage to the containment buildings.
- External surfaces that were included in the condition assessment [2], [3].
- Durability of the reinforcement and post-tensioning systems of the containment buildings.

Structural aspects, such as a reduction in load bearing capacity due to reinforcement corrosion, were not considered.

The repair strategies that are proposed in this report are based on the condition assessment completed to date on Containment Unit 2 and the dome of Unit 1.

The repair strategies developed for the containment structures may or may not be suitable for other structures at KNPS. Suitable repair strategies need to be developed for each individual structure based on individual condition assessments and performance requirements.

2. REFERENCES

The following documents are referenced within this document.

Document Title		Preparer / Author	Document Number	Revision or Date of Issue
[1]	Condition assessment of the containment buildings at KNPS: comparison between damage in 2000 and damage in 2014; performance of previously applied repairs	Prof. H. Beushausen	n/a	20 Oct 2014
[2]	Koeberg NPS, Non Destructive Testing of Containment Structures, Condition Assessment of Containment Domes	NSE	JN411-NSE-ESKB-R-4911	0
[3]	Koeberg NPS, Non Destructive Testing of Containment Structures, Condition Assessment of Containment Walls	NSE	JN411-NSE-ESKB-R-5567	Rev D
[4]	Concrete Repairs to External Surfaces of the Containment Buildings	Eskom	DSG-318-119	Rev 3
[5]	Evolution of repair strategies proposed for the containment buildings at KNPS	Prof. H. Beushausen	n/a	06 Oct 2014
[6]	Containment concrete durability monitoring strategy following patch repairs as per DSG 318-119	Eskom	DB2014-0016	20 Aug 2014
[7]	Prediction of future chloride ingress into the walls of Containment Building 2	Prof. H. Beushausen		10 Feb 2014
[8]	Products and systems for the protection and repair of concrete structures	European Standard	EN 1504:2004	2004
[9]	Cathodic Protection for the Containment Buildings – Basic Design Report	Expert Panel & NSE	JN465-NSE-ESKB-R-5703	0
[10]	Cathodic Protection for the Containment Buildings – Qualitative Modelling Report	Expert Panel & NSE	JN465-NSE-ESKB-R-5705	A

In addition to the above, the expert panel were given access to photographs of the containment buildings and the repairs as well as quality control documentation relating to the repairs. The following drawings were also made available (but were not fully reviewed due to time constraints).

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[11]	Containment Unit 1, Acoustic stress gauges, thermo elements, containment cylinder and dome, elevation and details	Spie Batignolles	KBA0106D01005	3
[12]	Reactor Building, Containment Cylinder, Unit 1, Vertical Section and developed elevation of perimeter beam formwork	Spie Batignolles	KBA1206D05001	1

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[14] Containment Unit 1 and 2, Dome principle of reinforcement	Spie Batignolles	KBA1206D06001 0.46/1652	2
[15] Reactor Building, Containment Cylinder Unit 1 and 2, Dome reinforcement of blocks N, O, P outside layer - square mesh, 1st bed	Spie Batignolles	KBA1206D06040	1
[16] Reactor Building, Containment Cylinder Unit 1 and 2, Dome reinforcement of blocks N, O, P outside layer - square mesh, 2nd bed	Spie Batignolles	Not evident on microfilm copy	1
[17] Containment Unit 1 and 2, Polar crane bracket, Location & principle of reinforcement	Spie Batignolles	KBA1206D04001 0.46/1651	2
[18] Reactor Building, Containment Cylinder Unit 1 and 2, Horizontal cabling, Precast Elements on Ribs, Typical reinforcement for elements 2R02 and 2L02	Spie Batignolles	KBA1206D04002	1
[19] Reactor Building, Containment Cylinder Unit 1 and 2, Precast elements for horizontal casing heads, Typical reinforcement for elements 4R02 and 4L02	Spie Batignolles	KBA1206D04003	1
[20] Containment Unit 1, Cylinder, Principle of reinforcement	Spie Batignolles	KBA0106D02011 0.46/1639	2
[21] Reactor Building, Containment Cylinder Unit 1, Reinforcement of concrete layers 1 and 2, Elevations of outside layer, Sections on Rib	Spie Batignolles	KBA0106D02063	1
[22] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts No 3-4-5, Outside layer elevation and sections (1st sheet)	Spie Batignolles	KBA0106D02061	1
[23] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts No 3-4-5, Intermediate layer elevation and sections (2nd sheet)	Spie Batignolles	KBA0106D02068	1
[24] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts No 3-4-5, Inside layer elevation and sections (3rd sheet)	Spie Batignolles	KBA0106D02069	2
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[26] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 18 and 19, inside layer elevation and sections	Spie Batignolles	KBA0106D04016	1
[27] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 18 and 19, intermediate layer elevation and sections	Spie Batignolles	KBA0106D04017	1

Document Title	Preparer / Author	Document Number	Revision or Date of Issue
[28] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 18 and 19, outside layer elevation and details	Spie Batignolles	KBA0106D04018	1
[29] Bending schedule	Spie Batignolles	KBA0106D04019	1
[30] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 20, 21, 22 inside layer	Spie Batignolles	KBA0106D04020 (parts 1 and 2)	1
[31] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 20, 21, 22 intermediate and outside layers	Spie Batignolles	KBA0106D04021	1
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[35] Reactor Building, Containment Cylinder Unit 1, Reinforcement of lifts 23, 24 intermediate and outside layers, elevations and sections	Spie Batignolles	KBA0106D04033	1
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[37] Stressing of containment	Spie Batignolles	KBA1206D01404	A
[38] Reactor Building, Containment Cylinder Unit 1, Vertical cabling and castings above level +30.00	Spie Batignolles	KBA0106D04012	2
[39] Reactor Building, Containment Cylinder Unit 1 Dome, Vertical section and developed elevation of perimeter beam, Formwork	Spie Batignolles	KBA1206D05001	1
[40] Reactor Building, Containment Cylinder Unit 1, Vertical cables in ribs from -5.00 to +30.00	Spie Batignolles	KBA0106D02053	1
[41] Containment Unit 1, Vertical cables deviation from level -10.00 until +30.00, between ribs 1 and 2	Spie Batignolles	KBA0106D02001	1
[42] Containment Unit 1, Vertical cables deviation from level -10.00 until +30.00, between ribs 2 and 3	Spie Batignolles	KBA0106D02002	1
[43] Containment Unit 1, Vertical cables deviation from level -10.00 until +30.00, between ribs 3 and 4	Spie Batignolles	KBA0106D02003	1
[44] Reactor Building, Containment Cylinder Unit 1, Casing heads for horizontal cables between 14.475 and 31.08 Rib 1 equipment hatch, horizontal sections	Spie Batignolles	KBA0106D02032	1

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[45] Reactor Building Unit 1 - General Assembly	Spie Batignolles	0.46/10649	20
[46] Reactor Building Unit 1 - General Assembly	Spie Batignolles	KBA0106F00002	1
[47] Reactor Building Unit 1 - Dome General Assembly	Spie Batignolles	KBA0106F00005	1
[48] Reactor Building Unit 1 - Steel Liner, Shell V3, Plate mark V3.3	Spie Batignolles	KBA0106F02042	20
[49] Reactor Building Unit 1 - Steel Liner, Shell V1, Plate mark V1.10	Spie Batignolles	KBA0106F02029	20
[50] Reactor Building Unit 1 - Steel Liner, Shell V1, Plate mark V1.8	Spie Batignolles	KBA0106F02028	20
[51] Reactor Building, Containment Cylinder Unit 1 and 2, Pendulums Setting Out	Spie Batignolles	KBA1206D01007	3
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[53] Containment Unit 1, Outside developed view along R=19.40 between levels -7.00 and +30.00, Crossing holes between ribs 2 and 3	Spie Batignolles	KBA0106D01002	1
[54] Containment Unit 1, Outside developed view along R=19.40 between levels -7.00 and +30.00, Crossing holes between ribs 3 and 4	Spie Batignolles	KBA0106D01003	1
[55] Containment Unit 1, Outside developed view along R=19.40 between levels -7.00 and +30.00, Crossing holes between ribs 4 and 1	Spie Batignolles	KBA0106D01004	1
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[61] Reactor Building, Containment Cylinder Unit 1, Personnel Lock at +1.15, Formwork	Spie Batignolles	KBA0106D01032	1
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[63] Containment 1, Personnel Hatch (+9.15), Route of the door through the BAN at +8.00	Spie Batignolles	KBA0106D01403 0.46/48852	1

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[65]	Reactor Building, Containment Cylinder Unit 1, Equipment hatch, Formwork elevation and vertical section in the axis	Spie Batignolles	KBA0106D01029	1
[66]	Reactor Building, Containment Cylinder Unit 1, Equipment hatch, Formwork horizontal sections	Spie Batignolles	KBA0106D01030	1
[67]	Reactor Building, Containment Cylinder Unit 1, Equipment hatch, Formwork vertical sections	Spie Batignolles	KBA0106D01033	1
[68]	Containment and handling gantry Unit 1, Positions of cradle for pressure test inspection access	Spie Batignolles	KBA0106D05413	A
[69]	Containment 20m Equipment Hatch	Spie Batignolles	KBA1206K031007	Z1
[70]	Containment Personnel Airlock	Spie Batignolles	KBA1206K031009	Z1
[71]	Reactor Building, Internal Structures, Unit 1, Level +8.92, Top View	Spie Batignolles	KBA0106H07001	3
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[73]	Reactor Building, Internal Structures, Unit 1, Level +4.65, Top View	Spie Batignolles	KBA0106H05002	1
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[75]	Reactor Building, Internal Structures, Unit 1, Level +8.92, Top View	Spie Batignolles	KBA0106H11002	3
[76]	Reactor Building, Internal Structures, Unit 1, Level +16.90, Bottom View	Spie Batignolles	KBA0106H11001	2
[77]	Reactor Building, Internal Structures, Unit 1, Level +12.00, Top View	Spie Batignolles	KBA0106H09002	2
[78]	Reactor Building, Internal Structures, Unit 1, Level +12.00, Bottom View	Spie Batignolles	KBA0106H09001	2
[79]	Reactor Building, Containment Cylinder Unit 1 Dome, Formwork, Plan View	Spie Batignolles	KBA0106D05003	1
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[83]	Reactor Building, Internal Structures, Unit 1, Level +0.00, BottomView	Spie Batignolles	KBA0106H03001	1
[84]	Reactor Building, Internal Structures, Unit 1, Mat plan view at level -3.50 theoretical, finishing details	Spie Batignolles	KBA0106H01002	2

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[85] Reactor Building, Internal Structures, Unit 1, Mat plan view at level -3.50 theoretical, Formwork	Spie Batignolles	KBA0106H01001	20
[86] Reactor Building, Internal Structures, Unit 1, Level +0.00, Bottom View	Spie Batignolles	KBA0106H00002	1
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[88] Reactor Building, Internal Structures, Unit 1, General Section 2.2	Spie Batignolles	KBA0106H00022	4
[89] Reactor Building, Internal Structures, Unit 1, General Section 3.3	Spie Batignolles	KBA0106H00023	3
[90] Reactor Building, Internal Structures, Unit 1, General Section 4.4	Spie Batignolles	KBA0106H00024	3
[91] Reactor Building, Internal Structures, Unit 1, General Section 5.5	Spie Batignolles	KBA0106H00025	20
[92] Reactor Building, Internal Structures, Unit 1, General Section 6.6	Spie Batignolles	KBA0106H00026	3
[93] Reactor Building, Internal Structures, Unit 1, General Section 7.7. Partial section 8.8.	Spie Batignolles	KBA0106H00027	20
[94] Containment Unit 2, Outside developed view along R=19.40 between levels -7.00 and +30.00 crossing holes between ribs 1 and 2	Spie Batignolles	KBA0206D01001	1
[95] Containment Unit 2, Outside developed view along R=19.40 between levels -7.00 and +30.00 crossing holes between ribs 2 and 3	Spie Batignolles	KBA0206D01002	1
[96] Containment Unit 2, Outside developed view along R=19.40 between levels -7.00 and +30.00 crossing holes between ribs 3 and 4	Spie Batignolles	KBA0206D01003	1
[97] Containment Unit 2, Outside developed view along R=19.40 between levels -7.00 and +30.00 crossing holes between ribs 4 and 1	Spie Batignolles	KBA0206D01004	1
[98] Reactor Building, Containment Cylinder Unit 2, ASG and TE raft, containment cylinder and dome elevation and detail	Spie Batignolles	KBA0206D01005	2
[99] Reactor Building, Containment Cylinder Unit 2,Formwork - tightness ribs (1st sheet)	Spie Batignolles	KBA0206D01022	3
[100] Reactor Building, Containment Cylinder Unit 2,Formwork - tightness ribs (2nd sheet)	Spie Batignolles	KBA0206D01023	3
[101] Reactor Building, Internal Structures, Unit 2, Level +8.92 Top View	Spie Batignolles	KBA0206H07001	1
[102] Reactor Building, Internal Structures, Unit 2, Level +8.92 Bottom View	Spie Batignolles	KBA0206H07002	3
[103] Reactor Building, Internal Structures, Unit 2, Level +4.65 Top View	Spie Batignolles	KBA0206H05002	2

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[104] Reactor Building, Internal Structures, Unit 2, Level +4.65 Bottom View	Spie Batignolles	KBA0206H05001	1
[105] Reactor Building, Internal Structures, Unit 2, Level +16.90 Top View	Spie Batignolles	KBA0206H11002	1
[106] Reactor Building, Internal Structures, Unit 2, Level +16.90 Bottom View	Spie Batignolles	KBA0206H11001	1
[107] Reactor Building, Internal Structures, Unit 2, Level +12.00 Top View	Spie Batignolles	KBA0206H09001	1
[108] Reactor Building, Internal Structures, Unit 2, Level +12.00 Bottom View	Spie Batignolles	KBA0206H09002	2
[109] Reactor Building, Containment Cylinder Unit 2, Dome Formwork, plan view	Spie Batignolles	KBA0206D05002	1
[110] Reactor Building, Internal Structures, Unit 2, Level +20.00 Upper plan view (rough level)	Spie Batignolles	KBA0206H13002	2
[111] Reactor Building, Internal Structures, Unit 2, Level +20.00 Bottom view	Spie Batignolles	KBA0206H13001	1
[112] Reactor Building, Internal Structures, Unit 2, Level +0.00 theoretical Top view, rough level	Spie Batignolles	KBA0206H03002	1
[113] Reactor Building, Internal Structures, Unit 2, Level +0.00 theoretical Bottom view	Spie Batignolles	KBA0206H03001	1
[114] Reactor Building, Internal Structures, Unit 2, Level -3.50 theoretical	Spie Batignolles	KBA0206H01001	2
[115] Reactor Building, Internal Structures, Unit 2, Plan view at +0.00	Spie Batignolles	KBA0206H00002	1
[116] Reactor Building, Internal Structures, Unit 2, General Section 1.1	Spie Batignolles	KBA0206H00021	3
[117] Reactor Building, Internal Structures, Unit 2, General Section 2.2	Spie Batignolles	KBA0206H00022	2
[118] Reactor Building, Internal Structures, Unit 2, General Section 3.3	Spie Batignolles	KBA0206H00023	2
[119] Reactor Building, Internal Structures, Unit 2, General Section 4.4	Spie Batignolles	KBA0206H00024	2
[120] Reactor Building, Internal Structures, Unit 2, General Section 5.5	Spie Batignolles	KBA0206H00025	2
[121] Reactor Building, Internal Structures, Unit 2, General Section 6.6	Spie Batignolles	KBA0206H00026	2
[122] Reactor Building, Internal Structures, Unit 2, General Section 7.7 and 9.9	Spie Batignolles	KBA0206H00027	1

3. STATE OF DETERIORATION OF THE CONTAINMENT STRUCTURES AT KNPS

Containment Unit 2 at KNPS is showing a progressed state of reinforcement corrosion damage. The following aspects summarize the Expert Panel’s assessment of the degree of deterioration:

- Significant rebar corrosion damage has developed since the condition assessment performed in 2002 [1]. This indicates that the structure is in an advanced state of corrosion propagation.
- In reinforced concrete structures with such a high degree of corrosion damage future damage can be expected to develop exponentially with time.
- Considerable additional rebar corrosion damage can be expected to develop in currently undamaged locations (in the near future). Substantial additional spalling may be observed in as little as 1-2 years from now.
- Unless prevented using a suitable repair strategy, corrosion damage to the post-tensioned (PT) ducts and subsequently, in the tendons can be expected in the future.
- A long-term repair strategy should be implemented as soon as possible to ensure that the functionality and serviceability of the containment structures are not compromised. The expert panel is unable to provide a reliable estimate as to the period that the containment buildings will still be able to meet their design basis due to the advanced state of chloride ingress and rebar corrosion.

4. REVIEW OF THE CONDITION ASSESSMENT OF UNIT 2

The Expert Panel reviewed the condition assessment that was carried out on containment Units 1 (dome only) and Unit 2 (references [2] and [3]) and came to the following general conclusions:

- The scope of the assessment (selected methodology, test methods) was well designed and corresponds to international standards and state-of-the-art procedures.
- The information generated (quantity and quality of data) is appropriate for the assessment of the state of general deterioration and reinforcement corrosion damage.
- The interpretation of test results is complete and meaningful and serves as a suitable basis for the design of appropriate repair strategies.

With particular emphasis on the condition of the PT system, the Expert Panel suggested to NSE and Eskom to perform additional assessment on the vertical anchor heads and the horizontal ducts:

- The vertical anchor heads (situated on the roof next to the domes) should be inspected for possible corrosion damage and the results of the inspection included in [2].
- The horizontal ducts should be exposed and visually inspected for corrosion damage in a few more locations in order to confirm that the ducts are still in good condition.
- The 2nd phase concrete placed around the dome anchor heads in the ring beam should be checked once the necessary access is provided.

5. REVIEW OF PATCH REPAIR SPECIFICATIONS AND PROCEDURES

5.1 REVIEW OF SPECIFICATIONS

The Expert Panel reviewed the current patch repair methodology (references [4] and [5]) and came to the following conclusions:

- The specified methodology (removal of deteriorated concrete, substrate surface preparation, migrating corrosion inhibitor application, reinforcement preparation, edge conditioning, installation of discrete sacrificial anodes, repair mortar application, curing, and surface coating application, etc.) corresponds to good practice and state-of-the-art patch repair procedures.
- The selection of a suitable repair mortar for shotcrete repair based on performance testing of various available materials follows very good practice.

5.2 LIMITATIONS OF THE PATCH REPAIR TECHNIQUE

Further, the Expert Panel advises on the following limitations of the patch repair technique:

- The methodology of patch repair will provide limited additional service life to the repaired areas only. Reinforcement corrosion will continue to propagate in unrepaired areas and result in future damage (delamination, spalling, etc.).
- The patch repairs will not be effective in protecting the PT ducts from chloride-induced corrosion.
- The patch repairs need to be supplemented with a suitable long-term repair strategy to provide a long-term durable repair solution.

5.3 INTEGRATION OF THE CURRENT PATCH REPAIR ON UNIT 2 INTO A LONG-TERM REPAIR STRATEGY

The Expert Panel discussed how the current patch repairs would fit into the proposed long-term repair strategy (cathodic protection (CP), as discussed in later sections) and concluded the following:

- The patch repairs are not expected to interfere with the functionality of the CP system (see [10] for further details). It will therefore not be required to remove the patch repairs (or any part of it) prior to installation of the proposed CP system.
- The specified coating can also be applied on the containment walls as it has been determined that this will not interfere with the CP system which will utilise anode strips. The coating should not be applied to the dome and ring beam as a paint applied anode will be used in these locations. This is based on the assumption that the CP system will be installed in the coming 2-3 years.
- The current patch repair methodology includes the painting of the reinforcing steel with a protective coating. This coating isolates the steel from the surrounding concrete and hence prevents electrolytic conduction between reinforcing steel and anode (once the CP system has been installed). The CP system will therefore not be able to protect the coated reinforcing steel from future corrosion. However, reinforcing steel that has been treated according to the specifications (i.e. cleaning of all rust and application of surface coating) will not need any protection by the CP system as it is already protected against future corrosion. Further, in areas where the patch repairs have not been completed according to the specifications (e.g. insufficient application of protective coating to the

reinforcing steel), the CP system will aid in providing corrosion protection. In patch-repaired areas, the CP system will therefore have no negative effect (see [9] for further details), but may have a positive effect where additional durability is required.

5.4 CONSTRUCTION (REPAIR) QUALITY CONTROL

On Monday, 03.11.2014, the Expert Panel performed a site visit to containment Unit 2 and inspected some of the areas that had been prepared for shotcrete application. It was noted that the preparation of the substrate area and reinforcing steel were not fully done according the specifications and did not fully correspond to good practice. Of particular concern were the preparation of patch boundaries (which were contaminated with paper bags), the contamination of the substrate concrete surface with the protective coating for the reinforcement, and insufficient or incorrect coating of reinforcing steel. With the observed lack of quality in repair area preparation, durable patch repair can probably not be achieved. Consequently, it is advised that better quality control is exercised to ensure repair specifications are followed properly.

As the contractor was not on site at the time of the expert panel inspection, it could not, however, be confirmed whether the exposed panels inspected had been completely prepared for shotcreting.

6. PERFORMANCE REQUIREMENTS FOR LONG-TERM REPAIR SOLUTION

In discussions with Eskom and NSE representatives, the Expert Panel developed performance requirements (PReq.) for the long-term repair system, as detailed below.

PReq. 1. Service life requirement: 40 years minimum

The repair solution needs to provide technical solutions for extending the service life of the structures until at least the year 2055. This service life includes for an additional 20 years of operation after the 40 year design life of the power station (10 years remaining) plus 10 years of decommissioning. According to Eskom this service life could be extended further.

PReq. 2. No future rebar corrosion damage

The repair system needs to fully arrest the development of future corrosion damage (delamination) in currently undamaged (and also in patch-repaired) areas. The main reason for this is that every excavation and delamination lowers the structural capacity of the containment buildings.

PReq. 3. Compatibility with penetrations

The repair system must not negatively affect penetrations.

PReq. 4. Compatibility with the remainder of the structure

The repair system must not negatively affect any part of the structure (e.g. the steel lining).

PReq. 5. Compatibility with the monitoring systems

The repair system must not interfere with current monitoring systems on the structure.

PReq. 6. Compatibility with the PT system

The repair system must not negatively affect the PT system.

Negative influences such as hydrogen embrittlement of PT steel (which is sometimes associated with CP systems) needs to be prevented.

It needs to be possible to remotely monitor the compatibility between the repair system and the PT ducts.

PReq. 7. Functionality during and after ILRT testing

The repair system needs to remain functional during and after ILRT testing. The system needs to withstand a maximum surface strain of roughly 800 x 10^{-6} without rupturing or debonding.

PReq. 8. Effective monitoring of repair performance

The monitoring of repair effectiveness needs to be done remotely.

Continuous monitoring of the repair system should not require access to vertical walls (this only applies to active systems such as CP systems but not to secondary systems such as overlays and coatings).

The monitoring system needs to detect corrosion activities on PT ducts.

PReq. 9. Resistance to environmental influences

The repair system must withstand adverse weather conditions, including direct sun and rain exposure, temperature and moisture cycles, strong winds, and lightning.

PReq. 10. Access restrictions during application

It is assumed that no access limitations for the application of the repair system exist, i.e. it is assumed that scaffolding can be provided if required.

PReq. 11. Resistance against high temperatures

In the area above the steam bunkers the repair system needs to be able to withstand a temperature of 300^oC (sustained over 3 days).

PReq. 12. Speed of installation

For the area above the steam bunkers, it would be beneficial (but not a requirement) to the station operation if the repair system could be installed in a period of 2 months.

PReq. 13. Visual appearance

The repair system needs to follow the current shape of the structure and preferably have a neutral external colour (colour is not a requirement).

PReq. 14. Corrosion prevention for post-tensioning ducts

The PT ducts appear to be non-galvanized and may have already been subjected to chloride-promoted corrosion prior to installation, as evidenced from construction photographs. In addition, the chloride threshold value for the metal used in the ducts may be lower than that for the reinforcing steel (this can only be confirmed once the composition of the metal has been identified (see Section 13); currently, no reliable information on the metal properties is available and it can therefore not be assumed that the PT ducts have the same chloride threshold value as the reinforcing steel). The repair system needs to therefore be able to prevent future corrosion of the metal PT ducts.

The Expert Panel was informed by Eskom that corrosion of the PT tendons would probably result in the end of the operational service life of the containment buildings at KNPS. The prevention of corrosion of the PT ducts and tendons is therefore of paramount importance for this project.

PReq. 15. Quality control during application

Proper and effective quality control during application of the repair system needs to be possible.

7. PRINCIPLES, LIMITATIONS AND APPLICABILITY OF VARIOUS REPAIR SOLUTIONS

7.1 REPAIR PRINCIPLES ACCORDING TO EN1504:2004

The Expert Panel discussed various repair system solutions and evaluated these against the performance criteria presented in Section 6 above. The guidelines given in the European Standard EN 1504:2004 [8] (*Products and systems for the protection and repair of concrete structures*) were used as a basis for the discussion. EN 1504 describes various repair principles for concrete structures damaged by chloride-induced reinforcement corrosion, as summarized in Table 1.

Table 1: Principles and remedial actions for concrete structures subject to reinforcement corrosion damage (summary based on EN1504:2004)

Repair principle	Repair system / material
Concrete restoration (CR): Restoring to the originally designed shape and function.	Hand-applied mortar. Recasting with concrete. Spraying concrete or mortar. Replacing elements.
Cathodic control (CC): Creating conditions in which potentially cathodic areas of reinforcement are unable to drive an anodic reaction.	Reducing oxygen supply at the cathode by saturation or surface coating.
Preserving or restoring passivity (RP): Creating chemical conditions in which the surface of the reinforcement is maintained in, or is returned to, a passive condition.	Increasing cover with additional concrete or mortar. Replacing contaminated or carbonated concrete. Electrochemical chloride extraction.
Cathodic protection (CP)	Impressed current systems (applying electrical potential), Galvanic systems (e.g. zinc anodes)
Control of anodic areas (CA): Creating conditions in which potentially anodic areas of reinforcement are unable to participate in corrosion reaction.	Painting reinforcement with coatings containing active pigments (e.g. zinc). Painting reinforcement with barrier coatings. Applying penetrating corrosion inhibitors to the concrete surface.

In order to identify the best suitable repair options for the containment buildings at KNPS, the Expert Panel evaluated whether the various repair solutions proposed in EN 1504:2004 meet the Performance Requirements (PReq.) identified in Section 6 above. Only methods that could be considered to have merits were discussed. Some methods were not applicable due to obvious practical or technical limitations (for example cathodic control by saturation, or large-scale increase of cover depth with additional concrete) and were therefore not considered.

Different repair solutions are evaluated in the following sections.

7.2 CONCRETE RESTORATION (CR)

The repair principle of concrete restoration is currently applied to the containment building Unit 2 in the form of patch repair (trowelled mortar, cast concrete, or shotcrete). This method is known to provide limited additional service life to reinforced concrete structures unless additional permanent repair solutions are installed. At KNPS, the patch repair is supported by discrete sacrificial anodes, which should provide the patch repairs with a service life in excess of 15 years (provided the repairs are executed according to the specifications). Practical experience shows that it is unlikely that the patch repairs will last for much longer than 20 years. This repair principle is therefore not suitable to provide the required long-term protection to the structures at KNPS. Further, concrete restoration is only able to reduce future corrosion damage in patch-repaired locations but is ineffective in preventing corrosion damage in non-patch-repaired locations. Extensive future repair of currently undamaged regions would therefore be required.

One of the main concerns for the containment structures is the condition of the PT ducts. Due to structural concerns, patch repair or concrete restoration can only be done to the surface of the containment buildings (to a maximum depth of about 70 mm). The method of concrete restoration is therefore not able to provide any protection to the PT ducts (which may already experience a certain degree of corrosion, compare explanation of PReq. 14 in Section 6).

Due to the above reasons the method of concrete restoration is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 1, 2, and 14.

7.3 CATHODIC CONTROL (CC)

The application of a surface coating to the structures at KNPS will only be effective in preventing or limiting further ingress of chlorides and moisture; serious doubts exist if it is possible to completely exclude oxygen access to corroding steel. This may reduce the corrosion rate of the embedded steel reinforcement but will not be effective in preventing future delamination and spalling. Further, this method is most likely unable to provide any protection to the PT ducts due to the large thickness of the structure that already contains sufficient amounts of oxygen, chlorides and water for corrosion propagation.

The ineffectiveness of this system to structures which have been exposed to a marine environment for 20+ years is demonstrated by the application of a specialist coating to the containment buildings in 2003. Despite this coating, widespread delamination occurred some 9 years later.

Due to the above reasons the method of cathodic control is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 1, 2, and 14.

7.4 PRESERVING OR RESTORING PASSIVITY (RP): REPLACING CONTAMINATED OR CARBONATED CONCRETE

Due to the progress of chloride penetration into the concrete, the complete replacement of chloride-contaminated concrete on the containment buildings is not possible. Large-scale removal of contaminated concrete would result in significant loss of structural capacity, which was deemed unacceptable by Eskom (compare explanation to PReq. 2 in Section 6). Further, in order to remove contaminated concrete at the level of the PT ducts, the ducts would have to be exposed, which would have a negative effect on their durability.

Due to the above reasons the method of restoring passivity by replacing contaminated concrete is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 2, 6, and 14.

7.5 PRESERVING OR RESTORING PASSIVITY (RP): ELECTROCHEMICAL CHLORIDE EXTRACTION

The method of electrochemical chloride extraction is commonly not advised for PT structures, due to the risk of hydrogen embrittlement and the associated risk to the structural and durability properties of PT steel. It is noted that the electrical current used in this method is significantly higher than that used for CP.

Due to the above reason the method of restoring passivity by electrochemical chloride extraction is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 6.

7.6 CONTROL OF ANODIC AREAS (CA): APPLYING PENETRATING CORROSION INHIBITORS TO THE CONCRETE SURFACE

Penetrating corrosion inhibitors (also termed migrating corrosion inhibitors (MCI)) may be effective in reducing the risk of chloride-induced reinforcement corrosion damage in concrete structures. However, significant disagreement exists amongst engineers and researchers with regards to the effectiveness of this method when applied to structures that are contaminated with chlorides. As a consequence of its limitations this method presently does not have a proven track record for successful repair of concrete structures subjected to chloride-induced reinforcement corrosion damage.

In general, MCI application is more likely to be successful in low-quality, porous concrete with low cover depths. The concrete in the containment structures at KNPS was found to be relatively dense and of high strength (compare references [2] and [3]). In addition, cover depths to the reinforcement exceed 40 mm in most locations. It is therefore unlikely that a MCI will successfully suppress reinforcement corrosion in the containment structures. Consequently, significant future rebar corrosion damage would be expected if this repair method was selected.

It is unlikely that the MCI would reach the PT ducts (at cover depths exceeding 80 mm) in sufficient quantity to provide any reliable protection.

Due to the above reason the method of control of anodic areas by applying MCI is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 1, 2, and 14.

7.7 CATHODIC PROTECTION (CP): GALVANIC SYSTEMS (E.G. ZINC ANODES)

The principle of reinforcement corrosion prevention using a sacrificial anode for cathodic protection relies on potential differences between the anode (e.g. zinc) and the reinforcement, so that the anode corrodes preferentially to the steel in the concrete.

The Expert Panel could not come to agreement with regards to the method's effectiveness for repair and prevention of steel corrosion in concrete. However, the Panel members agreed that galvanic systems would not be effective in reliably controlling rebar corrosion sufficiently to prevent future corrosion damage in the containment structures at KNPS. Further, it is unlikely that sufficient electric current density can be developed between the galvanic anode and the PT ducts, which renders the system potentially ineffective for protection of the ducts.

Moreover, in order to install galvanic anodes to protect the PT ducts, it would be necessary to exposed large parts of the ducts which would have a negative effect on their durability.

Due to the above reason the method of cathodic protection using galvanic systems is not suitable for the long-term repair of the containment structures at KNPS. This method cannot meet PReq. 14 and can probably not meet PReq. 1 and 2.

7.8 CATHODIC PROTECTION (CP): IMPRESSED CURRENT SYSTEMS

7.8.1 Conformity to Performance Requirements

The principle of cathodic protection using impressed current is the preferred solution for the long-term repair of the containment structures at KNPS. This system, if designed, installed and maintained correctly, meets all performance requirements outlined in Section 6, as detailed in the following paragraphs.

PReq. 1. Service life requirement: 40 years minimum

CP systems using impressed current have a proven track record of providing long-term reinforcement corrosion control in concrete structures (see Appendix D: Case studies of Cathodic Protection of concrete structures and Appendix E: Cathodic Protection of concrete structures: operating experience in the USA for reference projects). It is therefore expected that a properly designed, installed and maintained CP system will provide the containment buildings at KNPS with a remaining service life in excess of 40 years.

PReq. 2. No future rebar corrosion damage

The effectiveness of CP systems can be controlled through continuous monitoring of corrosion activities on the reinforcing steel and PT ducts. The electrical current density of the CP system can be adjusted to provide adequate protection to the steel even if boundary conditions (concrete moisture contents, temperature, structural deformations, etc.) were to change. Future corrosion damage to the reinforcing steel and PT ducts can therefore be prevented assuming that electrical connectivity exists between the rebar layers and PT ducts. Given the construction methodology where the vertical, horizontal and shear rebar layers are tied together with steel wire and the PT ducts sit on top of the shear rebar, electrical continuity can realistically be assumed to be present. This will however, be checked and recorded by on-site checks whenever PT ducts are exposed.

CP protection systems have a proven track record of preventing rebar corrosion damage (delamination, spalling) in reinforced concrete structures subjected to chloride-induced reinforcement corrosion.

PReq. 3. Compatibility with penetrations

The CP system can be designed to have a positive (i.e. protective) effect on metal penetrations in the containment walls. The effect (corrosion prevention) will be most dominant close to the external surface (where it would be most needed) and diminish towards increasing depths of the wall. (see [10] for further details)

PReq. 4. Compatibility with the remainder of the structure

The CP system can be designed to have a positive (i.e. protective) effect on metallic components of the containment walls, if required. No negative effects of the CP system on any metallic or non-metallic components of the containment walls are expected.

The detailed design of the CP system (which will be done at a later stage by a third party, i.e. not the Expert Panel) needs to further ensure the absence of stray-currents and the associated possibility of macro-cell corrosion.

PReq. 5. Compatibility with the monitoring systems

The CP system can be designed not to interfere with the present monitoring system of the structure. Adequate consideration can be given to the compatibility between existing monitoring systems and the CP system once detailed information on the monitoring systems (location, function, construction details) has been provided by Eskom.

PReq. 6. Compatibility with post-tensioning system

The effect of hydrogen embrittlement of PT steel can be prevented with the help of continuous monitoring. The principles of a suitable monitoring system to check compatibility between CP and the PT system were developed by the Expert Panel. (See Reference [9] for details.)

PReq. 7. Functionality during and after ILRT testing

The anodes of the CP system (suggested: titanium strips on the walls, as discussed further below) will be able to withstand a strain of 800 x 10^{-6} without rupturing. Debonding of the CP systems during or after ILRT testing can be prevented through the specification of suitable details, as discussed in [9].

PReq. 8. Effective monitoring of repair performance

The monitoring of the effectiveness of the CP system can be done remotely, without requirements to access the vertical walls of the containment buildings. A suitable monitoring system is designed to control corrosion of reinforcing steel and PT ducts. (See Reference [9] for details.)

PReq. 9. Resistance to environmental influences

The CP system can be designed to be sufficiently robust to withstand adverse weather conditions. Any weather-inflicted damage to the system can be monitored through routine inspections and continuous monitoring. The lightning protection system on each containment structure will be checked to ensure isolation from the CP system.

PReq. 10. Access restrictions during application

The CP system can most effectively be applied from scaffolding. Application from a cradle will be possible in locations where site conditions prevent the use of scaffolding.

PReq. 11. Resistance against high temperatures

In the detailed design of the CP system, special consideration will need to be given to this performance requirement. A suitable surface protection system may have to be developed for the affected locations above the steam bunkers.

PReq. 12. Speed of installation

Depending on site conditions during construction, the application of the CP system to the area above the steam bunkers within a period of 2 months should be possible. A suitable construction sequence needs to be developed by the appointed contractor.

PReq. 13. Visual appearance

The CP system can be designed not to affect the shape, dimensions and general appearance of the containment structures.

PReq. 14. Corrosion prevention for post-tensioning ducts

The steel reinforcement and PT ducts appear to be in physical contact, or at least to be connected through wire and other metal parts. The CP system (which will be connected to the reinforcement) is therefore expected to automatically have electrical connectivity to the PT ducts. Should this not be the case, connectivity between CP system and PT ducts can be provided.

Provided electrical connectivity is ensured, the CP system will effectively protect the ducts from corrosion (see [10] for further details). Considering all available repair solutions, CP based on impressed current is therefore the only system able to meet PReq. 14.

PReq. 15. Quality control during application

Standard quality assurance procedures are available for the installation of CP systems to reinforced and PT concrete structures.

Installation of the CP system needs to be done by an experienced contractor with experienced personnel. A requirement for the appointment of the contractor should be a proven track record of successful CP system installation to large and strategically important concrete structures, including prestressed / post-tensioned structures. A list of experienced contractors is included in Appendix C: List of recommended contractors for Cathodic Protection of concrete structures.

7.9 FIBRE-REINFORCED POLYMERS

Eskom asked the Expert Panel to comment on the suitability of using fibre-reinforced polymer (FRP) systems for the repair of chloride-induced reinforcement corrosion damage on the containment buildings. The following list summarizes the opinions expressed by the panel:

- FRP systems are not intended for the repair of reinforcement corrosion damage and do not provide a suitable solution.
- FRP systems are intended for the strengthening of concrete structures, which can be done in combination with reinforcement corrosion repair if required. However structural strengthening of the containment buildings is not required at this stage.
- With respect to preventing reinforcement corrosion, FRP systems would at best be as (in-) effective as surface coatings.
- FRP systems would not provide any additional service life to the containment structures. This is true especially in case of corrosion of PT tendons.
- FRP systems are not considered for reinforcement corrosion repair in any standards or guideline and have no applicability in this field.
- If FRP systems were applied as a reinforcement corrosion repair method to the containment structures at KNPS, future condition assessment and repair would be made impossible. The application of FRP to the structures would therefore significantly lower the remaining service life of the structures.

8. CP SYSTEM SOLUTIONS: PRINCIPLES AND APPLICATION METHODS

8.1 GENERAL CONSIDERATIONS

The proposed cathodic protection system works with the principle of using applied electrical current between an externally applied anode and the reinforcing steel. The established electrochemical process turns the reinforcing steel into the cathode and therefore prevents reinforcement corrosion. Other metal components in the concrete (PT ducts, penetrations, steel liner, etc.) will also be protected against corrosion as long as they have electrical connectivity to the reinforcing steel that is connected to the low voltage DC power supply (see also [10]). Cathodic protection has the added benefit of chloride removal from the vicinity of the steel, which further aids in providing long-term durability to the structures.

The principles of cathodic protection systems for reinforced concrete structures, case studies of successful applications, system components, installation procedures and quality control are discussed in Appendix D: Case studies of Cathodic Protection of concrete structures, Reference [10] and the literature provided in Appendix B: Selected literature for further reading and detailed information.

The main difference between various CP system solutions is the type of anode used. Three different systems were evaluated, as discussed in the following sections. The aim of the discussions was to identify the most suitable CP system solution from a technical (expected performance) and practical (application procedures) point of view. Further details on the design of the CP systems are presented in [9].

8.2 CP1: TITANIUM MESH PLUS CEMENTITIOUS OVERLAY

For this particular system, the anode consists of a titanium mesh (which has a structure similar to that of a chicken wire mesh) connected to the concrete surface with non-conducting (e.g. plastic) anchors. The anode is embedded in a conductive cementitious overlay (with a thickness of approximately 30 mm) which provides continuous electrolytic (i.e. ionic) connectivity between anode and concrete surface. A schematic of the system is presented in Figure 1.

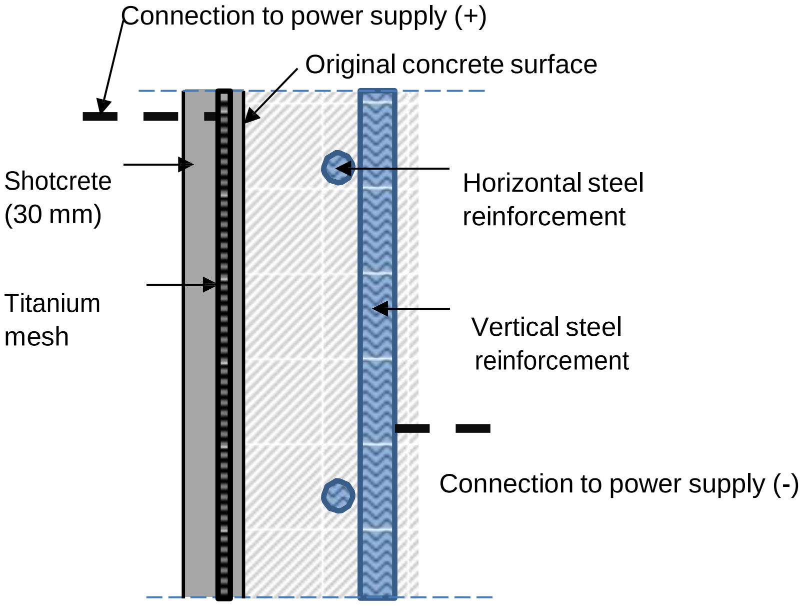

Figure 1: Schematic of CP system using titanium mesh plus cementitious overlay (approximately to scale), surface coating not shown

The following summarizes the basic construction procedures involved (power supply and monitoring systems are not considered in this list):

- Substrate surface preparation: sandblasting or water jetting to roughen and clean the surface. The aim is to achieve maximum bond strength between overlay and substrate.
- Mechanical fixing of titanium mesh.
- Overlay application.

The cementitious overlay can in principle consist of either trowel applied mortar, cast concrete or mortar, or shotcrete. However, trowel-applied mortar when applied over such a large surface would not have sufficient (durable) bond strength. Further, the casting of concrete would require formwork, which is not a practical solution for the size of the overlay. The recommended overlay application method would therefore be shotcreting.

8.3 CP2: TITANIUM STRIPS IN SLOTS, EMBEDDED IN CEMENTITIOUS MORTAR

The anode system consists of a titanium strips that are embedded in slots. The slots are situated between the horizontal reinforcing bars at regular spacing of about 200 mm across the height of the structure (the spacing corresponds to the spacing of the horizontal reinforcement). The slots are created by mechanically excavating the concrete surface to a depth of approx. 30 mm and width of approx. 30 mm. A schematic of the system is presented in Figure 2.

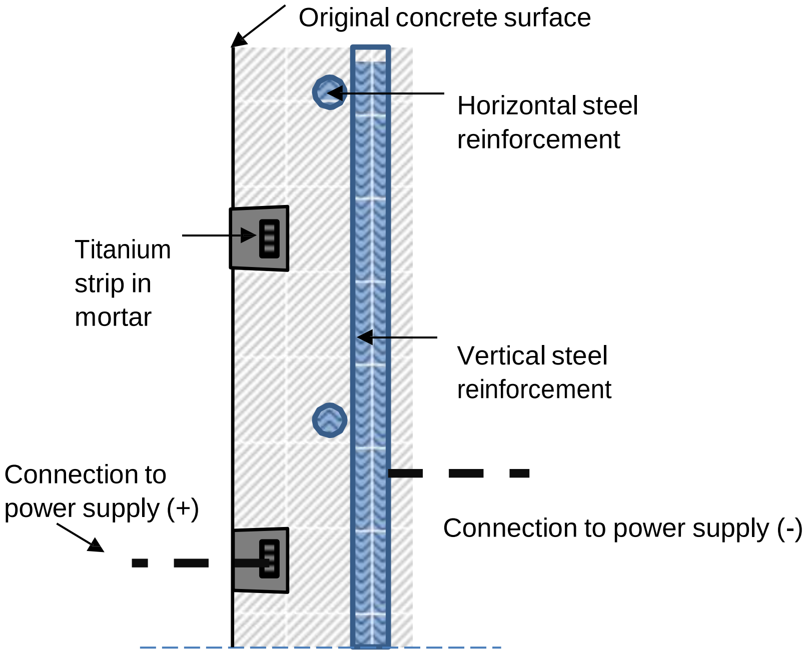

Figure 2: Schematic of CP system using titanium strips in slots (approximately to scale), surface coating not shown

The following summarizes the basic construction procedures involved (power supply and monitoring systems are not considered in this list):

- Cutting slots into the concrete surface using a specially designed mechanical tool.
- Installing the titanium strips into the slots by embedding them into a cementitious mortar; the mortar is finished off flush with the original concrete surface.
- Application of a surface coating for uniform appearance and repair area protection.

8.4 CP3: PLATINUM WIRES PLUS CONDUCTIVE COATING

The anode surface consists of a conductive coating in which platinum wires are embedded at regular spacing of approximately 1 m (either vertically or horizontally). The platinum wires provide the electrical current to the coating. A schematic of the system is presented in Figure 3.

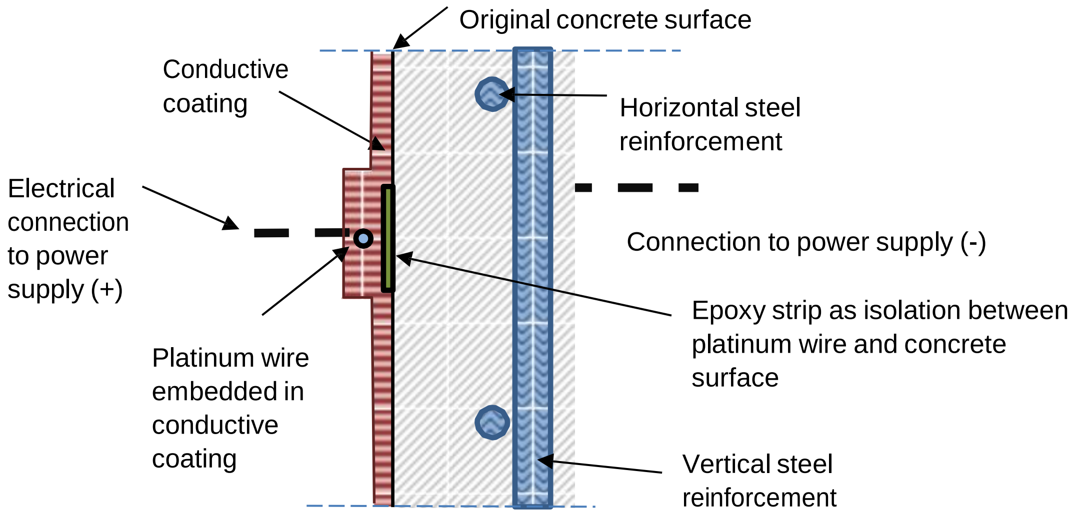

Figure 3: Schematic of CP system using conductive coating (conductive coating thickness not to scale), surface coating not shown

The following summarizes the basic construction procedures involved (power supply and monitoring systems are not considered in this list):

- Substrate surface preparation: sandblasting or water jetting to roughen and clean the surface. The aim is to achieve maximum bond strength between coating and substrate.
- Painting epoxy strips along the surface in regular spacing of approximately 1 m (either vertically or horizontally). The purpose of the epoxy strip is to prevent direct electrical connectivity between platinum wire and concrete surface.
- Application of the conductive surface coating to the whole surface area (incl. epoxy strip).
- Placement of platinum wires above the coated epoxy strip.
- Placement of a layer of conductive coating over the platinum wires; the wires are now fully embedded in the coating.
- Placement of a layer on non-conductive coating as protection.

8.5 COMPARISON OF CP SYSTEM SOLUTIONS

Each of the three possible CP systems discussed in Sections 8.2 to 8.4 has advantages and disadvantages for the repair of the containment structures at KNPS. These are summarized on a comparative basis in Table 2.

Table 2: Comparison of CP system solutions

Aspect	CP1: Titanium mesh and shotcrete	CP2: Titanium strips in slots	CP3: Conductive coating
Estimated service life until anode system needs replacement	20 years[1]	40+ years	15 years[2]
Adequate bond repair - substrate	Very difficult	Not difficult	Difficult
Excavations needed	no	yes	no
Additional load on structure	yes	no	no
Additional protection needed for temperature resistance (PReq. 11)	Yes	Probably not	Yes
Comparative complexity of installation (3 = most difficult to install properly)	3[3]	2	1
Estimated resistance to environmental influences (PReq.9) (ranking: 1 = best)	3[4]	1	2[5]
The system can be applied to all regions of the structure (access for installation is provided everywhere)	no	yes	yes
Cradle application	Not possible	Possible	Possible
Scaffold application	Possible	Possible	Possible
Rope access application	Not possible	(Possible)[6]	(Possible)[6]
Surface prep. is extensive and critical (ranking: 3 = most extensive and critical and difficult to achieve)	3	1	2
Estimated comparative time needed for installation (ranking: 1 = fastest)	3	2	1
The current coating needs to be removed (by sandblasting the whole surface)	yes	no	yes
Overall confidence that the system can be installed with sufficient quality and will be durable[7]	4/10	8.5/10	7.5/10

1. The service life limitation of CP1 relates to difficulties of ensuring durable bond strength between shotcrete and substrate
2. The service life limitation of CP3 relates to consumption and weathering of the conductive coating
3. The installation of shotcrete for the current patch repairs appears very problematic (access obstructions, quality control problems, some areas cannot be accessed, etc.). Application of shotcrete with consistent thickness seems not possible on the containment structures
4. Considering that the shotcrete will be applied to cover the whole surface of the structures, environmental influences such as wind, temperature cycles, and moisture cycles are expected to result in partial or full loss of bond between shotcrete and substrate in the longer term
5. Debonding under environmental influences would be a concern
6. Rope access application will be difficult but possible in areas where other forms of access cannot be provided
7. The confidence ranking was done by averaging the Expert Panel's individual rankings for a particular method. In the ranking, all aspects listed in Table 2 were considered

The main limitations associated with CP1 (titanium mesh and cementitious overlay) are that sufficient and durable bond strength between shotcrete and substrate will be very difficult to achieve. The durability of the system is therefore uncertain since it is controlled by the overlay bond. In addition, observations made during the site visit on 03.11.2014 (compare Section 5.4) indicate that the site conditions (access restrictions) are not suitable for application of a large-scale overlay. Also, the shotcrete can only be applied from scaffolding, which limits the method to certain locations of the structure. Other locations (where no scaffolding can be placed) would have to be repaired with another method. Such a “patchwork” method of cathodic protection is not preferred.

The main limitation associated with CP2 is that the cutting of slots may result in a loss of structural capacity. According to Eskom (represented by Derek Lee) this loss in structural capacity seems minimal because of the shallow depth of approx. 30 mm which represents a cross section loss of only 3% in the vertical direction and this occurs in the cover-crete (the slots are installed horizontally only). The influence of the slots on the structural capacity needs further investigation by Eskom.

The main limitation associated with CP3 is the expected service life duration of about 15 years, after which the system has to be fully removed and reinstalled. This is not practical especially for the vertical walls of the containment structures.

Notably, the Expert Panel’s ranking of the various system solutions indicates that systems CP2 and CP3 are the most suitable for the repair of the containment structures at KNPS. System CP1 is considered to offer a limited probability of successful repair.

8.6 SPECIAL CONSIDERATIONS

8.6.1 Impact of CP system on steel liner

The durability and functionality of the steel liner on the inside of the containment structure is of paramount importance. The possible influence that the CP system may have on the steel liner is summarized in the following:

- The CP system will have a positive influence (some level of corrosion protection) on all metal components inside the containment wall (including the steel liner), provided they have electrical connectivity with the outer reinforcement layer to which the CP current is supplied. (See [10] for further details)
- The level of protection provided from the CP system to metal components inside the wall will decease with increasing depth from the external surface. The effect on the steel liner is therefore expected to be minimal. (See [10] for further details)

As a consequence of the above aspects, the CP system is not expected to have any negative effect on the steel liner.

8.6.2 Impact of CP system on standard maintenance procedures

The CP systems will be applied to the concrete surface and may interfere with standard maintenance procedures (inspections, monitoring, fixing of components to the surface, etc.). Such interference needs to be minimized in the detailed design specifications for the repair system. To this effect, Eskom needs to provide the system designer / contractor with detailed information on maintenance requirements.

8.6.3 Importance of adequate maintenance and monitoring of a CP system

A CP system will only provide protection to the reinforcement if it is adequately maintained and monitored as it is not a passive system. This includes:

- Monitoring of current levels on a weekly basis.
- Testing for depolarization every three months
- Visual inspection once a year
- Replacement of defective power supplies within a reasonable amount of time (1 month after discovery)

Only if Eskom is committed to maintain an active approach to the monitoring system on their containment structures for the next 40 years, will a system such as the suggested cathodic protection work. As soon as the power is turned off, this system will stop offering protection.

9. PROPOSED LONG-TERM REPAIR SYSTEM SOLUTIONS

Based on the discussions presented in Section 8, the Expert Panel proposes the use of cathodic protection (impressed current) for the long-term repair of the containment structures at KNPS.

System CP1 (titanium mesh with cementitious overlay) is considered to offer limited durability, as discussed in Section 8.5, and is therefore not recommended.

9.1 REPAIR OF THE VERTICAL WALLS

Due to access restrictions, the most critical parts of the containment structures are the vertical walls, for which a system with minimum maintenance requirements and maximum durability is required. The proposed method of repair is CP 2 (titanium strips in slots).

Major corrosion damage on the containment structures is only occurring in locations above 15 m from the ground level. From a technical perspective it can therefore be considered to install the CP system only in regions above 15 m. The regions below 15 m could be protected by a surface coating which may help to slow down the ingress of chlorides, oxygen and moisture sufficiently to prevent future corrosion damage. However, Eskom Koeberg Management indicated in discussions that it is preferred to select a single repair method for the total wall area. The option of applying the CP system only to selected locations on the walls will therefore not receive any further consideration.

The CP is to be installed to both patch-repaired and unrepaired areas. The installation of the CP system to the patch repaired areas is intended to provide these areas with the maximum possible durability.

The condition assessment report [3] contains limited information on the condition of the horizontal PT anchors. This is due to the circumstance that detailed inspection of the anchors would involve exposing them to the environment, which is considered harmful to their durability. However, the condition assessment [3] indicates that all delaminations above the PT anchors have been identified and will be repaired. The CP system will prevent future corrosion of the PT anchors in patch-repaired and currently unrepaired areas, such that a more detailed assessment of the anchors will not be necessary.

Further details on the design of the CP system are provided in [9].

9.2 DOMES AND RING BEAM

For the dome and the ring beam on top of the vertical walls, CP 3 (conductive coating) is proposed for the following reasons:

- The reinforcement on the domes is placed across the dome in various directions, which makes the cutting of slots (CP 2) with regular distance between rebars impossible.
- Similarly, the changes in surface profile (curvature, corners, and edges) over the dome and ring beam will make the cutting of slots in appropriate locations difficult.
- The main limitation of CP 3 is the limited expected service life duration of approximately 15 years. Considering easy access on the domes, this limitation is of lesser importance for the domes, compared to the vertical walls.

Note that for optimum CP system performance, the ferrules in domes will probably need to be removed, unless they are connected to reinforcement.

Further details on the design of the CP system are provided in [9].

10. COMPLETION OF PATCH REPAIRS ON CONTAINMENT UNIT 2

The current patch repair specifications include materials to assist in providing maximum durability to the repairs, including the following:

- Protective surface coating on the steel.
- Migrating corrosion inhibitors.
- Discrete sacrificial anodes.
- Protective coating to the patch surface.

The CP system by itself will provide sufficient protection to the reinforcement in patch-repaired areas. Consequently the above four protective measures would not be required if the CP system was installed closely after patch repair.

However, in the meeting on 06.11.2014, Eskom Koeberg Management indicated that it is unlikely that the installation of a long-term repair system will commence before 2017. It is therefore recommended to make no changes to the current patch repair specifications for Unit 2.

For Unit 1, a more optimized repair solution can be developed. In this solution, patch repair and CP system should be designed and installed as a unit, not as two separate systems. This will provide practical and cost-effective solutions to the repair of containment Unit 1.

11. CONDITION ASSESSMENT OF CONTAINMENT UNIT 1

The Expert Panel discussed the impending condition assessment containment Unit 1 and came to the following recommendations:

- The complete structure should be subjected to a delamination survey.
- The complete structure should be subjected to a cover survey.
  - For practical reasons, the use of a GPR instead of a cover meter should be investigated. Details on GPR are provided in Appendix F: Ground Penetrating Radar for determination of cover depth.

- For the design of suitable repair options, Half-cell potential (HCP) mapping of the whole structure is not necessary. HCP testing can be performed in selected locations. These locations can be identified based on the outcome of the delamination survey and cover depth measurements.
  - The Expert Panel will develop a methodology for selection of locations for HCP measurements. This methodology will be presented in a separate document in January 2015.
- HCP measurements should be performed in the vicinity of the PT anchors.
  - A suitable methodology for this will be presented in a separate document in January 2015.
- The development of HCP in certain areas over a period of 1 – 2 weeks should be assessed to check possible external causes of potential variation versus daily operating conditions in the power station.
  - A suitable methodology for this, including interpretation criteria will be presented in a separate document in January 2015.
- For the design of suitable repair options, concrete resistivity measurements on the whole structure are not necessary. Resistivity testing can be limited to the same locations as HCP testing.
  - In addition to testing resistivity in-situ, testing should be performed on samples removed from the structure (e.g. delaminated sections) and prepared (pre-saturated) in the laboratory.
- The use of a robot for areas of difficult access should be considered. This will enable remote-controlled data collection (e.g. cover measurements).

12. REPAIR SPECIFICATIONS

The scope of the work includes the development of specifications for the cathodic protection systems. Separate specifications are developed for the vertical walls (CP 2) and the dome and ring beams (CP 3). The specifications are included in [9].

13. REPAIR MONITORING SYSTEM

The scope of the work includes the development of specifications for a CP monitoring system. Separate specifications are developed for monitoring the repair performance on the vertical walls (CP 2) and the repair performance on the dome and ring beams (CP 3). The specifications are included in [9].

14. FURTHER WORK REQUIRED

The list of items requiring further investigation includes the following:

- Estimation of chloride threshold values for the concrete used at KNPS. The issue of the chloride threshold will lose importance should CP be applied to the containment structures. However, it should still be determined to assist in the evaluation of other reinforced concrete structures on the power station.

The following additional information is required from Eskom:

- Condition assessment of vertical PT anchors at the elevation of the ring beam.
- Condition assessment of the ring beam.
- Information on the material composition of the PT ducts.

The following testing should be undertaken to further inform the design of the CP system:

- Further work on estimating / measuring the cover depths to the PT ducts.
- Testing the electrical resistivity of the repair mortars applied to Unit 2.

The following will be determined in consultation with CP contractors:

- Estimation of costs for the CP systems.
- Estimation of the construction time for CP installation on the containment structures.

15. CONCLUSIONS

The following conclusions are drawn:

- The containment structures at KNPS have reached a very advanced state of reinforcement corrosion damage.
- Future reinforcement corrosion damage in presently unrepaired areas is expected to develop exponentially with time and result in more widespread delamination.
- The end of the operational service life of the containment structures may be reached soon if future corrosion damage is not prevented through application of a long-term repair solution.
- The long-term repair solution needs to be able to protect both the reinforcing steel and the post-tensioning ducts from corrosion.
- The presently specified patch repair methodology follows state-of-the-art procedures and good practice for localised zones of degradation but will not provide protection to the overall containment structures for the required remaining service life of 40 years.
- Performance requirements for the long-term repair solution, specific to the containment structures, were developed and are stated in this report.
- The only available repair method to meet the defined performance criteria for the containment structures is cathodic protection (CP) based on impressed current.
- For the vertical walls of containment Unit 2, a CP system is proposed, which makes use of titanium strips (anodes) that are placed in horizontally cut slots on the wall surface. Details are provided in this report.
    - Note that the selection of a suitable CP system for the walls of containment Unit 1 needs to be done based on the impending condition assessment of Unit 1.
- For the ring beam and domes of containment Units 1 and 2, a CP system is proposed, which makes use of a conductive surface coating. Details are provided in this report.
- Comprehensive monitoring systems will need to be installed to control the performance of the CP systems.
- Routine monitoring and periodical testing of CP quality must be carried out.
- The CP system proposed for the domes and ring beam on Unit 2 will probably need replacement after approximately 15 years.

- Maintenance of the CP system on the wall may be expected after about 15 years, which should include checking and, if necessary, replacing all power supplies and data loggers / remote control units and other components.
- Routine monitoring and periodical testing of CP quality must be carried out followed by replacement of failing components (e.g. power supplies).
- The present patch repairs on containment Unit 2 should be completed according to the existing specifications.
- The quality control for the present patch repairs on containment Unit 2 needs to be improved.

16. RECOMMENDATIONS

The expert panel is unable to provide any estimation as to the period that the containment buildings will still be able to meet their design basis due to the advanced state of chloride ingress and rebar corrosion measured and observed on Unit 2. These measurements and local repairs must still be undertaken on Unit 1 containment. It is therefore strongly recommended that a long term protection system, in the form of impressed current cathodic protection, be implemented on both containment structures immediately after completion of local repairs.

It is recommended that Eskom establish a long-term contract or agreement with the CP contractor to do periodical testing of the CP quality and the replacement of failing components when required.

Appendix A: LIST OF ATTENDEES AT THE WORKSHOP MEETINGS

Table 3: Workshop attendees (a “1” indicates participation on the particular day)

NAME	ORGANISATION	Tues 04/11	Wed 05/11	Thurs 06/11	Fri 07/11
International Delegates :					
Prof R Polder	TNO, TU Delft	1	1	1	1
Prof M Nagi	American University, Dubai	1	1	1	1
Prof R Francois	INSA Toulouse	1	1	1	1
Dr Maria Guimaraes	EPRI	1	1	1	1
Samuel Johnson	EPRI	1	1	1	1
Local Delegates :					
Prof H Beushausen	UCT	1	1	1	1
D Lee	ESKOM	1	1	1	1
T Rylands	NSE	1	1	1	1
S Starck	ESKOM	1	1	1	1
M Koopman	ESKOM		1		
M Rahube	ESKOM	1	1		
B Francis	ESKOM	1	1	1	1
T Moila	ESKOM	1	1	1	1

Appendix B: SELECTED LITERATURE FOR FURTHER READING AND DETAILED INFORMATION

B.1 GENERAL

1. EN1504:2004, 'Products and systems for the protection and repair of concrete structures', European Committee for Standardisation, December 2004, 50 pp.
2. Polder, R.B., Leegwater, G., Worm, D, Courage, W. (2012), 'Working life of cathodic protection systems for concrete structures—analysis of field data', Concrete Repair, Rehabilitation and Retrofitting III, Alexander et al. (eds.), Proceedings ICCRRR 2012, Cape Town South Africa, ISBN 978-0-415-89952-9, pp. 504-510.
3. ISO 12696:2012, 'Cathodic protection of steel in concrete', European Standard, CEN – European Committee for Standardization, February 2012, 46 pp.

B.2 REFERENCES AND STANDARDS (ORIGIN OF DOCUMENTS: USA)

The references and standards listed below are the latest editions at the time this document was prepared. Since these documents are revised frequently, the reader is encouraged to contact the proper sponsoring group to obtain the latest version if applicable.

AASHTO

4. AASHTO T277 (latest revision), "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration", AASHTO, Washington, DC.
5. AASHTO T260 (latest revision), "Standard Method of Test for Determining Chloride Ions in Concrete and Concrete Materials by Specific Ion Probe", AASHTO, Washington, DC.
6. AASHTO T332 (latest revision), "Standard Method of Test for Sampling and Testing Chloride Ion in Concrete and Concrete Raw Materials", AASHTO, Washington, DC.

ACI INTERNATIONAL

7. ACI 222R-01 (latest revision), "Protection of Metals in Concrete Against Corrosion" ACI International, Farmington Hills, MI.
8. ACI 222.1 (latest revision), "Provisional Standard Test Method for Water-Soluble Chloride Available for Corrosion of Embedded Steel in Mortar and Concrete Using the Soxhlet Extractor", ACI International, Farmington Hills, MI.
9. ACI 318 (latest revision), "Building Code Requirements for Reinforced Concrete Structures", ACI International, Farmington Hills, MI.
10. ACI 349 (latest revision), "Code Requirement for Nuclear Safety Related Concrete Structures and Commentary", American Concrete Institute, Farmington Hills, MI.
11. ACI 350 (latest revision), "Code Requirement for Environmental Engineering concrete Structures and Commentary", American Concrete Institute, Farmington Hills, MI.

ASTM INTERNATIONAL

12. ASTM D 4580 (latest revision), “Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding”, ASTM International, West Conshohocken, PA.
13. ASTM C 876 (latest revision), “Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete”, ASTM International, West Conshohocken, PA.
14. ASTM G57-06 (latest revision), “Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method”, ASTM International, West Conshohocken, PA.
15. ASTM C 1152 (latest revision), “Test Method for Acid-Soluble Chloride in Mortar and Concrete”, ASTM International, West Conshohocken, PA.

AWS

16. AWS C2.20 (latest revision), “Specification for Thermal Spraying Zinc Anodes on Steel Reinforced Concrete”, American Welding Society, Miami, FL.

EPRI

17. EPRI Report 1025633, “Program on Technology Innovation: Chloride Attack-Induced Aging of Concrete Structures in the Energy Industry”, EPRI, Palo Alto, CA.
18. EPRI Report 1025627, “Program on Technology Innovation: Nondestructive Evaluation Inspection of Concrete Structures Subjected to Corrosion”, EPRI, Palo Alto, CA.
19. EPRI Report 3002000596, “Cathodic Protection Application and Maintenance Guide, Volume 2: Plant Structures and Equipment”, EPRI, Palo Alto, CA.

ICRI

20. ICRI Guideline 510.1-2013, “Guide for Electrochemical Techniques to Mitigate the Corrosion of Steel for Reinforced Concrete Structures”, ICRI, Rosemont, IL.

NACE INTERNATIONAL

21. NACE SP0308-2008, “Inspection Methods for Corrosion Evaluation of Conventionally Reinforced Concrete Structures”, NACE International, Houston, TX.
22. NACE International Publication No. 24234, “Report on Corrosion Probes in Soil or Concrete”, NACE International, Houston, TX.
23. NACE SP0187-2008, “Design Considerations for Corrosion Control of Reinforcing Steel in Concrete”, NACE International, Houston, TX.
24. NACE SP0107-2007, “Electrochemical Realkalization and Chloride Extraction for Reinforced Concrete”, NACE International, Houston, TX.
25. NACE SP0290-2007, “Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures”, NACE International, Houston, TX.

26. NACE SP0408-2008, “Cathodic Protection of Reinforcing Steel in Buried or Submerged Concrete Structures”, NACE International, Houston, TX.
27. NACE Publication 01105, “Sacrificial Cathodic Protection of Reinforced Concrete Elements - A State-of-the-Art Report”, NACE International, Houston, TX.
28. NACE Standard Test Method TM0294-2007, “Testing of Embeddable Anodes for Cathodic Protection of Atmospherically Exposed Steel Reinforced Concrete” NACE International, Houston, TX.
29. NACE Publication 01105, “Sacrificial Cathodic Protection of Reinforced Concrete Elements – A State-of-the-Art Report”, NACE International, Houston, TX.
30. NACE SP0100-2014 “Cathodic Protection to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water or Waste Water Service”, NACE International, Houston, TX.

The above Standards may be obtained from the following organizations:

American Association of State Highway and Transportation Officials (AASHTO)
444 N. Capital Street NW, Suite 249
Washington, DC 20001
www.transportation.org

American Concrete Institute (ACI International)
38800 Country Clun Drive
Farmington Hills, MI 48331
www.concrete.org

EPRI
3412 Hillview Avenue
Palo Alto, CA 94304
www.epri.com

ASTM International
100 Bar Harbor Drive
West Conshocken, PA 19428
www.astm.org

American Welding Society
8669 NW 36 Street, #130
Miami, FL 33166-6672
www.aws.org

International Concrete Repair Institute
10600 West Higgins Road, Suite 607
Rosemont, IL 60018
www.icri.org

NACE International
1440 South Creek Drive
Houston, TX 77084
www.nace.org

Appendix C: LIST OF RECOMMENDED CONTRACTORS FOR CATHODIC PROTECTION OF CONCRETE STRUCTURES

This appendix was prepared by Prof R. Polder and Prof M Nagi.

Contractors having experience with post-tensioned structures and/or slotted systems and coating systems include:

a. Company: Care4concrete.nl, Stadskanaal, The Netherlands
Contact person: Jan Leggedoor, http://www.care4concrete.nl/

b. Company: Vogel Kathodische Bescherming, Zwijndrecht, The Netherlands
Contact person: Hans van den Hondel,
http://www.vogel-kb.nl/kathodische_bescherming.html

c. Company: Concrete Repairs Ltd., Mitcham Surrey, UK
Contact person: John Drewitt, www.concrete-repairs.co.uk

d. Company: Freyssinet Ltd., Telford Shropshire,. UK
Contact person: Zoe Stokes, www.freyssinet.co.uk
Note: This is the UK based company; local Freyssinet subsidiary may be contacted

e. Company: Structural Preservation, USA
Contact person: Jorge Costa, www.structural.net

f. Company: CORRPRO, USA
Contact: www.corrpro.com/Contact-Corrpro.aspx

g. Company: C-probe
Contact person: Graeme Jones, gjones@c-probe.com and www.c-probe.co.uk

h. Company: Aegis Technical System LLC
Contact person: Calvin R. Pynn, pynndxb@eim.ae

Appendix D: CASE STUDIES OF CATHODIC PROTECTION OF CONCRETE STRUCTURES

This appendix was prepared by Prof R. Polder.

D.1 GENERAL

A number of case studies of CP application is reported, either of structures provided with similar anode systems as the ones specified for the containment structures at KNPS, or of structures with similar construction principles (post-tensioning).

D.2 SEVEN APARTMENT BUILDINGS IN THE NETHERLANDS

This case concerns seven identical apartment buildings dating from the late 1950s with corrosion due to mixed-in chlorides and partial carbonation in Groningen, The Netherlands. Between 1993 and 1999, the gallery slabs and frames were provided with CP by applying a conductive coating anode and a cosmetic top coat; more information is provided in [1]. The repair materials used had a resistivity matching the parent concrete. The primary anode to feed current into the coating was based on a silver wire mesh. The concrete with conductive coating and subsequently with top coat applied is shown in Figure 4.

In 2013, the operation and performance of the CP systems were investigated. It appeared that all had been operated at a constant voltage of about 2.0 Volts, the maximum voltage specified by the coating supplier. Current densities were low (below 1 mA/m^2 of concrete surface) and depolarisation was systematically below 100 mV, the minimum value required by the Standard [2]. Nevertheless, visual signs of corrosion or concrete damage were largely absent. Primary anodes, which apparently were not durable in use, had deteriorated to some extent. This case shows that despite some degradation of primary anodes and a generally low current density, causing depolarisation being below the standard's performance criterion, CP is able to provide long term protection of steel and concrete. However, this should not be taken as proof that less than 100 mV depolarisation should in general be accepted.

Figure 4: Apartment building with conductive coating and isolation for primary anode applied (left) and finished surface with top coat applied (right)

D.3 POST-TENSIONED BRIDGE END BEAM, THE NETHERLANDS

This case concerns two parallel post-tensioned bridges of 14 m width each, locally suffering from corrosion due to de-icing salt leakage in the abutment joints, near Den Bosch, The Netherlands. CP was installed in 1996 on a total of 56 m^2 of concrete surface [1]. Chloride had penetrated deeply into the underside of the bridge deck (end beam) over about half a metre from the joint. In the end beams, the post-tensioning steel was lying at a depth from the underside of at least 250 mm. A conductive coating anode plus top coat was applied to a zone of one meter wide from the joint and a silver wire mesh primary anode was installed parallel to the joint. The final situation is shown in Figure 5. The presence of prestressing steel was taken into account during the design of the system. Sixteen RE's for monitoring the absolute potential of the post-tensioning were installed at the depth of the ducts, of type manganese/manganese dioxide. Close to the mild steel reinforcement, sixteen graphite RE's (decay probes) were placed for normal protection monitoring. The monitoring frequency is four times per year. The criteria were as follows:

- protection of reinforcing steel: (average) depolarisation in 24 h > 100 mV
- absolute potential of prestressing steel: (all individual) polarised potentials more positive than -850 mV vs Ag/AgCl; considering the scatter in the base potentials of the RE's, it was decided to set the safety limit 50 mV more positive than is necessary according to [2].

Performance records up to 2011 show that the system works, although at low levels of depolarisation. Silver wire/coper cable connections have been replaced after 8 years.

Figure 5: Post-tensioned end beam with conductive coating CP applied

D.4 POST-TENSIONED BEAM HEADS, THE NETHERLANDS

In 2013-2014 thirty motorway bridges in the Netherlands with the same type of post-tensioned deck beams were provided with CP based on conductive coating with platinum wire primary anodes, without top coat [3]. Beam head reinforcement had developed corrosion due to de-icing salt leaking from overlying expansion joints. The main concern was the durable integrity of post-tensioning anchors and ducts/tendons. A total of 1300 beam heads were protected over one meter length. In each of the beams a decay probe and a true reference electrode were embedded. Monitoring results indicated that depolarization of reinforcing steel was sufficient, and that potentials of post-tensioning anchors and ducts stayed well away from critical levels [3]. A system for remote control and monitoring was installed. The CP contractor was awarded a maintenance and monitoring contract for 20 years.

The final situation is shown in Figure 6.

Figure 6: Conductive coating (black) CP applied to ends of post-tensioned bridge deck beams and stainless steel conduits to power supply box

D.5 BRIDGE CROSS BEAMS, THE NETHERLANDS

Reinforced concrete cross beams supporting a bridge deck near Leiden, The Netherlands, had developed corrosion due to de-icing salt leakage through cracks in the overlying deck. Damage to concrete was repaired and an anode system based on 20 mm wide titanium strips in horizontal slots in the concrete surface was installed in 2009. The strip capacity was calculated based on a design current demand of 20 $mA/m^2{}_s$ for (corroding) outer reinforcement and 5 $mA/m^2{}_s$ for inner rebar. Cover depth was typically 40 mm, with local values less than 30 mm; spots with a cover of less than 30 mm were isolated using epoxy coating.

Measurements in 2010 indicated an overall satisfactory level of depolarisation; however, significant variation occurred between the 18 reference electrodes; and one data logger unit malfunctioned. Figure 7 shows a beam being provided with slots and cabling.

Figure 7: Reinforced cross beam with slots cut

D.6 [redacted] NUCLEAR POWER PLANT, USA

Source: [4], [redacted]

Structures Protected: Reinforcing Steel in Seawater Intake Structure.

An impressed current system was installed in phases (during refueling outages) to cathodically protect the intake floor slab, circulating water pump bowels and salt water pits of the seawater intake structures. The installation was completed and the system commissioned in November 2007. The system consists of the ELGARD™ 150 (0.75" / 20 mm wide) titanium anode ribbon and the ELGARD™ 300 titanium anode mesh installed within various surfaces of the repaired concrete structure. In addition, ground wires, reference electrodes, conduit, wiring, rectifiers, and resistor control boxes were necessary to complete the system. The system is divided into nine (9) zones that correspond to specific areas of the structure. The installation consisted of anode ribbon installed at 12" (300 mm) on centre. In areas where the concrete was replaced, the anode ribbon was attached but isolated from the exposed top mat of reinforcing steel with plastic rebar clips and covered with concrete (see Figure 8). In areas of sound concrete the ribbon mesh was installed in slots at 12" on center and covered with a cementitious grout. Anode Mesh was also installed on the floor in areas of sound concrete and covered with a 1" thick concrete overlay. Reference electrodes were installed throughout the structure which allow for measurements indicating the level of protection on the reinforcing steel. The reference electrodes were installed at the level of the second (deeper) mat of reinforcing steel. Protection at this level will ensure protection to all reinforcing steel. A lead wire from each reference electrode as well as a ground wire from the reinforcing steel terminates in the reference electrode test station adjacent to the rectifier. The DC output of the nine (9) rectifiers ranges from 2.0 to 7.3 Volts and 1.07 to 2.64 Amps.

Operating Experience:

The system is presently operating and controlling corrosion of the reinforcing steel in the intake structures in accordance with NACE criteria for CP [5]. The life of the catalyzed anode mesh and ribbon mesh is expected to exceed 35 years. Periodic monitoring and maintenance by power plant staff is required to ensure continuous operation of the rectifiers.

Figure 8: Titanium Ribbon Mesh Anode installed in Concrete Repair using Plastic Rebar Clips (Source: Corrpro Companies, Inc.)

D.7 [redacted] PLANT (FOSSIL FUEL)

Source: [4], [redacted]

Structures Protected: Reinforcing Steel in Units 4 & 5 Hyperbolic Cooling Towers.

An impressed current titanium ribbon mesh slotted system and a discrete titanium mesh probe anode system was installed for the Units 4 & 5 Hyperbolic Cooling Towers. A slotted titanium ribbon mesh system was installed for CP of the reinforcing steel in both towers. In the lower (thicker) sections of the towers, the slotted anode system is supplemented with discrete titanium probe anodes that were drilled into the concrete. The probe anodes allow for deeper penetration of the protective current to the inner mat of reinforcing steel. The system is designed with one (1) rectifier for impressed current cathodic protection of both towers. Each tower is divided into 88 individually controlled anode zones. To provide DC power and reference electrode potential monitoring, the zones have been grouped together into 16 distributed rectifier outstations. In total, there are 88 zones rated at 15V/3A per tower. The system was commissioned in 2010. The average reported current density for the slotted titanium ribbon mesh system is 0.65 mA/ft^2 (7 mA/m^2_s) for the outer mat of steel and 0.28 mA/ft^2 (3 mA/m^2_s) for the inner mat of steel. The average reported current density for the discrete titanium probe anode system is 1.4 mA/ft^2 (15 mA/m^2_s) for the outer mat of steel and 0.46 mA/ft^2 (5 mA/m^2_s) for the inner mat of steel. In total there are 352 embedded reference electrodes for each tower (704 in total). Approximately 75% of the reference electrodes are Ag-AgCl (true reference electrodes) and the remaining reference electrodes (25%) are pseudo MMO titanium reference electrodes (activated titanium decay probes). Figure 9 and Figure 10 are photographs of the installed system.

Operating Experience:

According to [redacted] some areas of the impressed current system are not receiving full CP (100 mV of polarization decay) in accordance with NACE criteria [5]. In addition it would be preferred that the distributed outstations for the 8 upper zones be installed at a lower elevation, as these require maintenance and are susceptible to lightning surges and damage.

In addition it is estimated that approximately 10.5% of the permanently embedded Ag-AgCl reference electrodes have failed or are presumed to have failed. This is a significant number considering the age of the system. Additional quality control and testing should have been conducted during installation to ensure successful installation of these monitoring devices.

Some more experience is reported through an interview with a site engineer.

Figure 9: Slotted Titanium Ribbon Mesh Anode System and Probe Titanium Anode System ([redacted])

Figure 10: Installation of an Impressed Current System on a Hyperbolic Cooling Tower ([redacted])

Cooling towers (interview with an engineer on site)

Other CP application methods – What methods were evaluated?

- Conductive coating: was not chosen because of the low durability of this system.
- Titanium mesh and shotcrete: They had tested before in other applications and could not get a good bonding with the shotcrete. They do not have confidence that it will last.
- The application of Ti-mesh and shotcrete is not as controlled as the ribbons in slots and there is the risk of short circuit, particularly in cooling towers where there are so many metallic anchors embedded all over the place.
- Titanium ribbons in slots: seemed like the best and most durable option.

Lessons learned:

- [redacted] *Cooling tower* had 88 zones and that implied a lot of wires and control boxes (called distributed outstations). Some of those boxes are located in high areas that if they need to be repaired would have access problems. They recommend that those boxes are located at easy access locations.
- [redacted] *cooling tower.* After 4 years, 10% of electrodes failed (some of those during installation). They do not have confidence that the electrodes will last as much as the system is designed for. They are looking at options of what to do. The problem is that they do not have a plan for replacing those electrodes,
- [redacted] *cooling tower.* Cost overrun. The only reason for cost overrun was that while they were installing it, they realized that there were more areas delaminated than they originally thought, and those had to be repaired. Other than that, no other surprises.
- [redacted] *cooling tower and Jacksonville.* Maintenance: They have a service agreement with the same company that installed the system for monitoring and maintenance. (cost in the range of $20K to $30K/cooling tower/year – note that the area of a cooling tower is much larger than the containment)
- Company that installed the systems is Structural Preservation. The same company installed the systems in [redacted] [redacted] [redacted]. I believe they have offices in Dubai and Abu Dhabi, but most of their work is in the US.
- [redacted] Are coal plants, so no regulatory issues.

D.8 REFERENCES

[1] Polder, R.B., 1998, Cathodic Protection of Reinforced Concrete Structures in The Netherlands - experience and developments, HERON, Vol. 43, no. 1, 3-14

[2] EN-ISO 12696:2012, Cathodic protection of steel in concrete, CEN, Brussels

[3] Klamer, E., Gulikers, J., Hondel, H. van den, Polder, R.B., 2014, Liggerkoppen kathodisch beschermd, Cement 7, Beam heads cathodically protected, *in Dutch*

[4] EPRI, CP Operating experience in the US, from EPRI report 3002003090

[5] SP0290-2007, Impressed current Cathodic Protection of reinforcing steel in atmospherically exposed concrete structures, NACE

Appendix E: CATHODIC PROTECTION OF CONCRETE STRUCTURES: OPERATING EXPERIENCE IN THE USA

Extracts from EPRI report 3002003090 relating to operating experience in power stations and transportation bodies are included in this Appendix. It is noted that the EPRI representatives on this Expert Panel were in no way involved in the compilation of this report.

1

OPERATING EXPERIENCE

The following is a summary of relevant case histories and operating experience for cathodic protection systems that have been installed in reinforced concrete structures at nuclear power plants, fossil fuel power plants and structures outside the power generating industry.

5.1 [redacted] Nuclear Generating Station

Owner: [redacted]

Location: [redacted]

Structures Protected:

A. Submerged Portion of Reinforced Concrete Cooling Tower Columns in the Power Block. There are 9 forced-draft cooling towers site-wide (3 for each unit). Each tower consists of 49 internal support columns. The base of the reinforced concrete columns are continuously exposed to aggressive chemicals in the cooling water (treated sewage water). The system consists of one 32-lb bare high potential magnesium anode that is attached to the reinforced steel at the base of each column using the anode lead wire (see Figure 5-1 below). APS visually inspect the galvanic anodes during refueling outages (every 18 months) and replace any anode that has lost significant mass. Typically 1/3 of the anodes are replaced every outage. APS do not have any test sites to monitor system performance. All inspections are visual.

Figure 5-1.
Galvanic Anodes at Base of Cooling Tower Columns
(Source: [redacted])

A. Submerged Portion of Clarifiers and Thickeners in Water Reclamation Facility (WRF). The WRF is a tertiary treatment plant that reclaims treated secondary effluent water from the cities of Phoenix, Glendale and Tolleson. The facility includes six 140-ft dia. primary clarifiers, six 125-ft dia. secondary clarifiers and two 7-ft dia. first stage thickeners that were cathodically protected with impressed current systems. The system consisted of 14 air-cooled rectifiers with submerged (suspended) high silicon cast iron and platinum anodes that were installed in the mid-1980s. Water samples were tested to have the following properties: chloride concentrations range between 299 and 305 ppm, resistivity ranges between 529 to 578 ohm-cm, and pH ranges between 8.2 and 10.2.[1] The intent of the CP system was to protect the submerged metallic components of the clarifiers and thickeners from corrosion. In addition any reinforcing steel bars in the concrete floors and walls that are electrically continuous with the metallic components would also receive protective current. The system operated for approximately 5 years and was subsequently turned-off.

B. Reinforcing Steel of Cooling Tower Structure. A trial installation of a conductive coating impressed current system that was installed on one reinforced concrete cooling tower structure in the mid-1990s. The intent of the system was to protect the reinforcing steel in the atmospherically exposed concrete, such as the beams and column support structures. Shortly after energization the conductive coating dis-bonded from the concrete surface and the system was subsequently turned-off and removed.

Operating Experience:

A. Based on the results of delamination surveys (sounding of concrete) that are being conducted during the power outages, the galvanic anodes are providing adequate current to control corrosion of the reinforcing steel at the base of the submerged concrete columns in the cooling towers of the Power Block.

B. The impressed current CP systems for the clarifiers and thickeners in the WRF were removed from service during the early 1990s. An internal Technical Memorandum concluded that corrosion damage would be insignificant in high pH, relatively low chloride and sulfate environments. However conventional repairs are presently being used to deal with the ongoing corrosion problem and the plant is currently assessing the need and cost implications for installation of a CP system.

C. The trial installation of a conductive coating impressed current CP system for corrosion control of the reinforcing steel at a cooling tower in the Power Block was not deemed successful. The system was subsequently de-commissioned and removed.

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[1] Accurate Corrosion Control, Inc. (ACCI) report dated August 30, 2012, “Corrosion Engineering Services - Cathodic Protection Pre-Design Assessment for 12 Clarifiers and 2 First Stage Thickeners at the Arizona Public Services (APS) Palo Verde Water Reclamation Facility, ACCI Project #2059”.

5.2 [redacted] Nuclear Power Plant

Owner: [redacted]

Location: [redacted]

Structures Protected:

A. Reinforcing Steel of Circulating Water Conduits. A galvanic aluminum anode CP system was installed to protect the reinforcing steel in the Diablo Canyon circulating water conduits. Each of the 2 units has two 12-ft x 12-ft reinforced concrete tunnels which provide seawater for the main condenser and auxiliary cooling. The tunnels vary in length from 1,350 to 1,610 ft. A galvanic anode system consisting of 140-lb aluminum anodes (Galvalum™ III alloy) was designed and installed in the mid-1990s to control corrosion of the reinforcing steel in the tunnel walls.[1] The anode core is bolted to the reinforcing steel. PG&E visually inspect the galvanic anodes during refueling outages and replace any anode that has lost significant mass. According to PG&E the anodes at the ends of the tunnels are consuming faster because of the increased steel density. The anodes that are located remote from the ends of the tunnels (where the steel density is less) last approximately 10-20 years. Figure 5-2 provides a view of a partially consumed aluminum anode. A monitoring system was installed, however the anodes are shorted to the reinforcing steel and therefore anode current measurements and polarization decay testing cannot be performed.

Figure 5-2.
Galvanic Anode in Circwater Cooling Tunnel
([redacted])

Reinforcing Steel in Seawater Intake Structure. An impressed current system consisting of thermally spray zinc was installed on a trial basis to cathodically protect the reinforcing steel in a seawater concrete intake structure. The zinc anode was applied as a coating to the atmospherically exposed concrete surfaces above the water line. The system was energized in 2003 and was subsequently removed from service in 2006 due to

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[redacted] [redacted]

A. anode consumption. Figure 5-3 provides a view of an anode connection failure due to water leakage and oxidation inside a junction box.

Figure 5-3.
Thermally Sprayed Zinc Anode Connection Failure in Seawater Intake Structure
(Source:)

B. Reinforcing Steel in Seawater Intake Structure. The submerged portion of the reinforced concrete intake structures are cathodically protected with an impressed current system which consists of inert anodes that are submerged in the seawater. The intent of the CP system is to protect the submerged metallic components of the traveling screens, bar locks and gates from corrosion. In addition any reinforcing steel bars in the concrete floors and walls that are electrically continuous with the metallic components of the intake structures will also receive protective current. The system consists of 12 rectifiers with graphite anodes that are immersed in the seawater. The graphite anodes are consuming slowly and are now being replaced with MMO titanium anodes.

C. Concrete Repairs in Seawater Intake Structure. Point type zinc galvanic anodes have been installed in the concrete repair material of the atmospherically exposed sections of the seawater intake structures. The “hockey puck” anodes are installed at approximately 12” on center to form a grid (see Figure 5-4). Unfortunately a corrosion monitoring system was not installed during construction and no updates on system performance are available.

Figure 5-4.
Point Type Zinc Anodes installed in Concrete Repair of Seawater Intake Structure
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Operating Experience:

A. The galvanic aluminum anode CP system that was installed in the Diablo Canyon circulating water conduits is functioning as designed and controlling corrosion of the reinforcing steel. According to PG&E testing of the concrete surfaces by sounding with hammers indicates that delamination of the concrete is minimal.

B. An impressed current system consisting of thermally spray zinc that was installed on a trial basis to cathodically protect the atmospherically exposed sections of a reinforced concrete intake structure failed and was subsequently abandoned in place. Failure was attributed to zinc anode consumption and excessive oxidation of the anode connection plates.

C. The submerged portions of the seawater intake structures are cathodically protected using an impressed current system with inert anodes that are immersed in the seawater. Since the existing graphite anodes are starting to consume slowly, they are periodically being replaced with MMO titanium anodes. PG&E monitor the DC output of the rectifiers on a monthly basis to ensure continuous operation of the CP system.

D. Point type zinc galvanic anodes have been installed in the concrete repair material of the atmospherically exposed sections of the seawater intake structures. Unfortunately a corrosion monitoring system was not installed and no data is available to evaluate the level of protection on the reinforcing steel or life expectancy of the anode system.

5.3 [redacted] Nuclear Power Plant

Owner:

Location:

Structures Protected:

Reinforcing Steel in Seawater Intake Structure. An impressed current system was installed in phases (during refueling outages) to cathodically protect the intake floor slab, circulating water pump bowels and salt water pits of the seawater intake structures. The installation was completed and the system commissioned in November 2007. The system consists of the ELGARD™ 150 (0.75” wide) titanium anode ribbon and the ELGARD™ 300 titanium anode mesh installed within various surfaces of the repaired concrete structure. In addition, ground wires, reference electrodes, conduit, wiring, rectifiers, and resistor control boxes were necessary to complete the system. The system is divided into nine (9) zones that correspond to specific areas of the structure. The installation consisted of 150 anode ribbon installed at 12” on center. In areas where the concrete was replaced, the anode ribbon was attached but isolated from the exposed top mat of reinforcing steel with plastic rebar clips and covered with concrete (see Figure 5-5). In areas of sound concrete the ribbon mesh was installed in slots at 12” on center and covered with a cementitious grout. ELGARD 300 Anode Mesh was also installed on the floor in areas of sound concrete and covered with a 1” thick concrete overlay. Reference electrodes were installed throughout the structure which allow for measurements indicating the level of protection on the reinforcing steel. The reference electrodes were installed at the level of the second (deeper) mat of reinforcing steel. Protection at this level will ensure protection to all reinforcing steel. A lead wire from each reference electrode as well as a ground wire from the reinforcing steel terminates in the reference electrode test station adjacent to the rectifier. The DC output of the nine (9) rectifiers ranges from 2.0 to 7.3 Volts and 1.07 to 2.64 Amps.

Operating Experience:

The system is presently operating and controlling corrosion of the reinforcing steel in the intake structures in accordance with NACE criteria for CP. The life of the catalyzed anode mesh and ribbon mesh is expected to exceed 35 years. Periodic monitoring and maintenance by power plant staff is required to ensure continuous operation of the rectifiers.

Figure 5-5.
Titanium Ribbon Mesh Anode installed in Concrete Repair using Plastic Rebar Clips
[redacted]

5.4 [redacted] Nuclear Power Plant

Owner: [redacted]

Location: [redacted]

Structures protected:

Reinforcing Steel in Seawater Intake Structure. A thermally sprayed zinc anode impressed current cathodic protection was installed in 2006 to protect the reinforcing steel in the atmospherically exposed sections of the seawater intake structures. The system failed and was subsequently replaced in 2012 with a similar system which consisted of new rectifiers and fewer anode zones. Failure was attributed to zinc anode consumption and excessive oxidation of the anode connection plates.

Operating Experience:

The thermally sprayed zinc anode impressed current CP system that was installed for corrosion control of the atmospherically exposed sections of the intake structures failed after approximately six years of service. Failure was attributed to zinc anode consumption and excessive oxidation of the anode connection plates.

5.5 [redacted] Power Plant (Fossil Fuel)

Owner: [redacted]

Location: [redacted]

Structures Protected:

A. Reinforcing Steel in Units 4 & % Hyperbolic Cooling Towers. An impressed current titanium ribbon mesh slotted system and a discrete titanium mesh probe anode system was installed for the Units 4 & 5 Hyperbolic Cooling Towers. A slotted titanium ribbon mesh system was installed for CP of the reinforcing steel in both towers. In the lower (thicker) sections of the towers, the slotted anode system is supplemented with discrete titanium probe anodes that were drilled into the concrete. The probe anodes allow for deeper penetration of the protective current to the inner mat of reinforcing steel. The system is designed with one (1) rectifier for impressed current cathodic protection of both towers. Each tower is divided into 88 individually controlled anode zones. To provide DC power and reference electrode potential monitoring, the zones have been grouped together into 16 distributed rectifier outstations. In total, there are 88 zones rated at 15V/3A per tower. The system was commissioned in 2010. The average reported current density for the slotted titanium ribbon mesh system is 0.65 mA/ft^2 for the outer mat of steel and 0.28 mA/ft^2 for the inner mat of steel. The average reported current density for the discrete titanium probe anode system is 1.4 mA/ft^2 for the outer mat of steel and 0.46 mA/ft^2 for the inner mat of steel. In total there are 352 embedded reference electrodes for each tower (704 total). Approximately 75% of the reference electrodes are Ag-AgCl and the remaining reference electrodes (25%) are pseudo MMO titanium reference electrodes. Figures 5-5 and 5-6 are photographs of the installed system.

B. Lintels and Support Columns of the Units 4 & 5 Hyperbolic Cooling Towers. A galvanic zinc anode mesh Lifejacket® system was designed and installed for the lintels and support columns of the Units 4 & 5 hyperbolic cooling towers. For this method, structural steel brackets were first mounted to the exterior and interior surfaces along with steel rods to suspend the grillage formwork and jacket. Using an aerial lift, the jackets were attached to the lintel beams and columns, and a high strength cementitious grout was pumped through ports on the face of the jackets to encapsulate the zinc anode mesh. Eight (8) additional reference electrodes were installed for Lifejacket system. Figure 5-7 is a photograph of the installed system.

Operating Experience:

A. According to [redacted] some areas of the impressed current system are not receiving full CP (100 mV of polarization decay) in accordance with NACE criteria. In addition it would be preferred that the distributed out stations for the 8 upper zones be installed at a lower elevation, as these require maintenance and are susceptible to lightning surges and damage. In addition it is estimated that approximately 10.5% of the permanently embedded Ag-AgCl reference electrodes have failed or are presumed to have failed. This is a significant number considering the age of the system. Additional quality control and testing should have been conducted during installation to ensure successful installation of these monitoring devices.

A. Of the 160 support columns that are protected by the LifeJacket system, only 10% are monitored. Of the 16 monitored columns, approximately 75% have more than 100 mV of polarization development from the native potential values.

Figure 5-6.
Slotted Titanium Ribbon Mesh Anode System and Probe Titanium Anode System

[redacted]

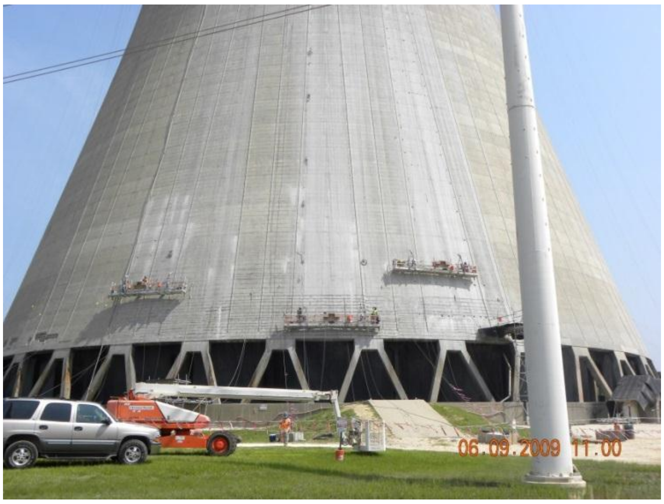

Figure 5-7.
Installation of an Impressed Current System on a Hyperbolic Cooling Tower

[redacted]

Figure 5-8.
Lifejacket System for Lintel Beam and Support Columns

[redacted]

5.6 [redacted] Power Plant (Fossil Fuel)

Owner: [redacted]

Location: [redacted]

Structures Protected:

A. Reinforcing Steel of Units 1 & 2 Hyperbolic Cooling Towers. An impressed current system was installed for CP of the Units 1 & 2 Hyperbolic Cooling Towers. A slotted titanium ribbon mesh system was installed for CP of the reinforcing steel in lower and upper sections of both towers. In the lower (thicker) sections of the towers, the slotted anode system was supplemented with discrete titanium probe anodes that were drilled into the concrete. The probe anodes allow for deeper penetration of the protective current to the inner mat of reinforcing steel. The system was commissioned in early 2014.

B. Lintels and Support Columns for the Units 1 & 2 Hyperbolic Cooling Towers. A galvanic zinc anode mesh Lifejacket® system was designed and installed for the lintels and support columns of the Units 1 & 2 hyperbolic cooling towers. The scope of work included installation of the Lifejacket system on 120 lintel beams and 240 columns for a total of 34,000 ft^2 of jacketing. Procedures included removing delaminated concrete, profiling concrete surfaces, cleaning corroded rebar, placement of the zinc anode mesh with integral fiberglass jackets and grouting in place. For this method, structural steel brackets were first mounted to the exterior and interior along with steel rods to suspend the grillage formwork and jacket. Using an aerial lift, the jackets were attached to the lintel beams and columns, and a high strength cementitious grout was pumped through ports on the face of the jackets to encapsulate the zinc anode mesh.

Operating Experience:

There is no operating experience to report for the impressed current system or the zinc anode mesh Lifejacket system.

5.7 [redacted] Highway Commission

Owner: [redacted]

Location: The majority of bridges with CP are located in the St. Louis and Kansas City areas

Structures Protected:

Bridge Decks and Bridge Substructures. Approximately 161 bridge decks and six bridge substructures have been retrofitted with impressed current CP systems. The majority of the decks with CP systems are box girder construction. Bridges with box girder construction are considered good candidates for CP since replacement of a deteriorated deck would require replacement of the entire superstructure. The earlier systems are slotted systems with platinized niobium wire and a conductive polymer grout that was developed by the Federal Highway Administration (FHWA). The conductive polymer grout system is now obsolete. The newer systems use catalyzed titanium ribbon mesh and anode mesh. The oldest system is approximately 25 years in age.

Operating Experience: [redacted] has a formal team to handle CP system design, installation oversight, monitoring and maintenance. The state has developed standard specifications for design and installation of the CP systems.

5.8 [redacted] Department of Transportation

Owner: [redacted])

Location: [redacted]

Structures Protected:

Bridges in Coastal Marine Environments. [redacted] have over 6,000 bridges in coastal marine environments. In the early 1980s, [redacted] determined that conventional repairs were not adequate for the rehabilitation of chloride contaminated concrete structures. [redacted]'s approach was to provide life extension to the affected structures by using CP and concrete rehabilitation. The cause and magnitude of corrosion activity is determined prior to design of rehabilitation and the type of CP system is determined based on the needs of the structure. CP systems used by [redacted] include:

- Catalyzed titanium anode mesh encapsulated in shotcrete or mortar.
- Catalyzed titanium anode mesh encapsulated in structural reinforced concrete.
- Catalyzed titanium anode mesh in conventional piles jackets.
- Thermally sprayed zinc anode (sacrificial protection).

- Zinc mesh anodes in conventional pile jackets.
- Submerged bulk anode systems (zinc or aluminum).

Operating Experience: [redacted] has found the CP is a cost effective method for providing life extension of bridge substructure components in marine environments. [redacted] does not use standard specifications for CP. However they do have a workgroup and corrosion laboratory that provides corrosion condition assessments, recommendations for corrosion control and technical support for cathodic protection systems. Highlights of implementation include:

- Structural analysis and evaluation of deterioration.
- Rehabilitation of concrete and reinforcement as necessary.
- Implementation of corrosion control measures which may include impressed current CP or sacrificial (galvanic) anode protection.
- Routine inspection of the structure, monitoring and maintenance of the CP system.

5.9 Parking Garage in [redacted]

Location: Underground parking structure in [redacted]

Structures Protected:

Reinforcing Steel in Parking Structure. A point type galvanic anode system using “hockey pucks” was installed along the expansion joints and in the structural slab at column bases to protect the reinforcing steel from corrosion. The structural slab is heavily contaminated with chloride ions (de-icing salts) that are brought into the garage from vehicles during the winter months. The anodes are installed in a low slump portland cement concrete that was used as the repair material.

Operating Experience:

Approximately 7 years after installation, several of the anode sites were excavated for inspection. The inspection found that the zinc anode inside the proprietary mortar encapsulation had totally consumed and no protection was being afforded to the reinforcing steel.

5.10 Parking Garage in [redacted]

Location: Multi-level parking facility in [redacted]

Structures Protected:

Reinforcing Steel in Parking Decks. The parking facility was built in 1970 was initially subject to corrosion of the reinforcing steel from de-icing salts that are brought into the garage from vehicle traffic. After installation and evaluation of several trial CP systems, the owner and structural engineer elected to embark on a full scale installation using catalyzed titanium ribbon mesh in slots. Since 1989, approximately 500,000 ft2 of elevated deck slabs have been cathodically protected using a slotted titanium ribbon mesh impressed current CP system. The 0.5” wide ribbon mesh is installed in 1” deep x 0.5” wide slots at 12” on center and backfilled with a non-shrink cementitious grout.

Operating Experience:

Since installation of the CP systems, field surveys conducted by the structural engineering consultant and corrosion engineer have indicated a high level of corrosion protection to the reinforcing steel in the concrete decks and a significant reduction in delamination growth. In areas of the slab where deck cracks pass through the anode slots, the cementitious grout backfill in the slots is replaced with a 4” length of epoxy compound to reduce the anodic current density and potential for acid generation at the anode-grout interface.

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LESSONS LEARNED

The following is a summary of lessons that have been learned based on experience with corrosion mitigation measures for reinforced concrete structures in various environments.

1. Chlorides are the most common source of concrete contamination that can lead to corrosion of the reinforcing steel and can often result in severe deterioration (cracking, delamination and spalling) of the building structure. The reinforcing steel in cooling towers, intake structures and water treatment facilities are particularly subject to this form of corrosion. Plants that are subject to chloride induced corrosion are typically located in coastal marine environments, although deterioration may also occur on structures at plants where treated sewage water is used for cooling.
2. In some situations there is a strong economic and technical case for including some form of corrosion mitigation technique within a concrete building repair project to ensure the condition of the structure is controlled and service life extension is provided.
3. CP is a technology that has been used for decades to control corrosion of reinforcing steel in concrete bridges, parking decks and building structures. If properly designed and maintained, the technique is the only method that is capable of totally reversing the electrochemical phenomena causing corrosion.
4. Plants and agencies that have successfully implemented CP technology have experienced a reduction in the frequency and cost of maintenance to the structure and an increase in the service life. To accomplish this they needed an applied understanding of the technology and the requirements for monitoring and maintenance.
5. Historically, unsuccessful applications of CP have been related to poor monitoring and maintenance practices, problems with rectifiers, premature anode consumption and poor track record with new technologies.
6. There are two forms of CP: a) impressed current systems, and b) sacrificial or galvanic anode systems. Impressed current systems require careful design and arrangement of the components. Furthermore a commitment by the owner is required to monitor and maintain the system. The level of protection afforded a concrete structure by an impressed current system is typically much greater than that of a galvanic anode system. However galvanic anodes are more simplistic in design and do not require the same level of monitoring and maintenance.

7. Galvanic anode performance is greatly influenced by the relative humidity and the level of moisture content in the concrete. Because of the high resistivity that is typical of concrete, discrete galvanic anodes (sometimes referred to as hockey pucks) are typically not recommended for CP, as the high resistivity limits the current delivery and protection criteria for CP may be difficult to achieve. Furthermore based on operating experience life expectancy could be minimal. These anodes are best suited for concrete patch repair to minimize the macro-cell corrosion effect between reinforcing steel in the new concrete and existing chloride contaminated concrete.
8. When using thermally sprayed zinc as an impressed current anode, all anode connection plates should be coated with an epoxy compound to prevent water ingress, oxidation and consumption at the anode feed points.
9. When installing Ag-AgCl reference electrodes in reinforced concrete structures, additional quality control measures and testing should be conducted during installation to ensure successful installation of these monitoring devices. Reference electrodes should be encapsulated in a portland cement grout with a resistivity value less than 15,000 ohm-cm. Testing should be conducted prior to and after installation of the reference electrode to ensure a stable and accurate structure-to-concrete potential.
10. Corrosion of the steel liners in containment buildings have been observed on the interior and exterior surfaces that are in contact with the concrete at a number of nuclear power plants. Electro-chemical techniques such as CP are not considered practical for corrosion control of these embedded steel liners. The steel rebar density in the containment wall is too high to consider galvanic anode protection and impressed current systems would require drilling multiple holes deep within the concrete wall to allow installation of probe type anodes; which ultimately could compromise structural integrity of the containment. For this reason conventional concrete and liner repair methods are recommended.

Recommendations for Further Work

Based on the results of this study and discussions with various utility representatives, consultants and contractors the following recommendations are provided for further work:

- Procedures, protocols and methodologies should be better defined to determine if a concrete structure is a good candidate for a particular corrosion control strategy.
- An engineering document could be prepared which outlines factors that most likely determine which corrosion control strategy is best suited for a structure. Factors to consider may include: a) quantity of damage, b) presence of chloride ions, c) extension of service life, d) life-cycle costs, e) cost of repair and rehabilitation, f) disruption to operations, g) structure type, and h) past experience with corrosion control systems.

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[1] Accurate Corrosion Control, Inc. (ACCI) report dated August 30, 2012, “Corrosion Engineering Services - Cathodic Protection Pre-Design Assessment for 12 Clarifiers and 2 First Stage Thickeners at the Arizona Public Services (APS) Palo Verde Water Reclamation Facility, ACCI Project #2059”.

[2] Simon, P., Sudhakar, A., Garrity, K. “Cathodic Protection of Steel Reinforced Concrete Circulating Seawater Conduits at a Nuclear Power Generating Plant”, Paper No. 237, NACE Corrosion/97.

Appendix F: GROUND PENETRATING RADAR FOR DETERMINATION OF COVER DEPTH

This appendix was prepared by Dr. M.Guimaraes.

F.1 INTRODUCTION

Ground Penetrating Radar can be used to perform cover depth surveys in concrete structures. ASTM standards and the ACI 228. R guideline provide information regarding the capabilities and limitations on the use of GPR in concrete structures and geophysical applications. These documents outline some of the advantages and limitations of the use of GPR in concrete structures. The user should be knowledgeable of the standards and guidelines before performing the process described in this document.

The following process describes the necessary steps to perform a correlation of the cover depth measurement with the two way travel time. For this process the following assumptions are made:

- Concrete is assumed to have the same general properties within the area surveyed
- Internal relative humidity of the concrete within the depth of cover is assumed to be uniform
- The antenna used for the GPR is of the same frequency during the survey and correlation

Manufacturers of GPR equipment have procedures to perform calibrations within the equipment based on the velocity of the electromagnetic wave. It is up to the operator to decide which method is better for their application.

F.2 PRINCIPLE

The method is based on the propagation and reflection of electromagnetic waves through a media. The equipment consists of an operating unit and an antenna that serves as a transmitter and a receiver. The antennas operate at different frequencies depending on the material in question. The most commonly used antennas for concrete investigations range between 900 MHz and 2600 MHz. Figure 11 presents a 1600 MHz commercially available system typically used for evaluation of concrete embedments.

Figure 11: Commercially available GPR unit with a 1600 MHz antenna.

The main parameters used to identify features embedded within a material are the dielectric constant of the material and the measurement of the time that it takes the waves to travel through a media and return to the antenna. If the waves traveling thru the media encounter the boundary of another material with a significantly different dielectric constant, the waves reflect back to the antenna. The time that it takes the waves to travel, from the antenna and back, can be correlated to the material and its depth. In the case of signals used for the evaluation of reinforced concrete the three materials that are fundamentally involved in the analysis of GPR signals. Air, concrete and steel are typical materials found in concrete investigations and their dielectric constant values are 1, between 4 and 11, and infinite, respectively. Steel has an infinite dielectric constant due to its conductive properties. Over the last 15 years the technology and applications of GPR have come a long way. Modern technology allows for data collection with encoder wheels that control the rate of sampling. Large numbers of individual signals can be compiled and presented in a colour coded format to recreate an image of the embedded reflectors along the scan path.

F.3 EQUIPMENT

Ground penetrating radar equipment with frequencies of 1600MHz, 2000MHz or 2600MHz should be used for performing measurements of the two way travel time to the depth of rebar for cover surveys. These antennas are commonly used for concrete investigations and should be used according to the manufacturer’s recommendations. Based on information from ASTM D4748-10 “Standard test method for determining the thickness of bound pavement layers using short pulse radar” antennas emmiting short pulses containing a centre of frequency of 2.0 GHz (2000MHz) and higher provide resolution sufficient for determination of a minimum layer thickness less than 25mm to an accuracy of ± 2.5mm. For measuring cover depths of 25 mm or less care must be taken due to the potential break on the surface reflection. Additionally, some equipment manufacturers have procedures for establishing in-situ correlations.

F.4 IDENTIFICATION OF THE RANGE OF COVER DEPTH

The range of cover depth to be surveyed should be established by the operator by reviewing construction drawings and conditions in the field. The operator will use individual cover depth measurements and perform a correlation of the two way travel time at the same location where the cover depth was obtained.

F.5 COLLECT SCANS AND PERFORM DIRECT MEASUREMENTS

After identifying the cover depth range, the operator will select a minimum of 5 points in which a direct correlation between the actual cover depth and the two way travel time will be established. It is preferable to get more than 5 points to develop a higher level of confidence. Further, it is important to keep the correlation points spread through the cover depth range for the correlation to be representative. For example, if the cover depth range in question is between 25mm and 120mm it is ideal to get a measurement at 25 mm, another at 120 mm and the remaining three points spaced in between. Perform a scan at each one of the locations selected (individual pieces of rebar).Mark and document the location and the file name where each one of the scans was performed. After performing the scans, drill to the depth of the rebar with a hammer drill and or a core drill to expose the rebar. Measure the depth of cover of the rebar to the nearest mm. and document the measurement performed in such way that it can be referenced during the analysis and correlated with the file recorded at the corresponding location. Repair the holes using a material of similar properties than the in-place concrete or a material that will prevent external agents from damaging the exposed piece of rebar.

F.6 PERFORM A CORRELATION BETWEEN COVER AND TWO WAY TRAVEL TIME

The operator needs to be cognizant of the surface reflection (first positive reflection on the wiggle plot) and the reflections of the reinforcing steel (Figure 12). The reflection to the steel reinforcement, in this case will be the secondary and strongest positive reflection in the wiggle plot at the rebar location.

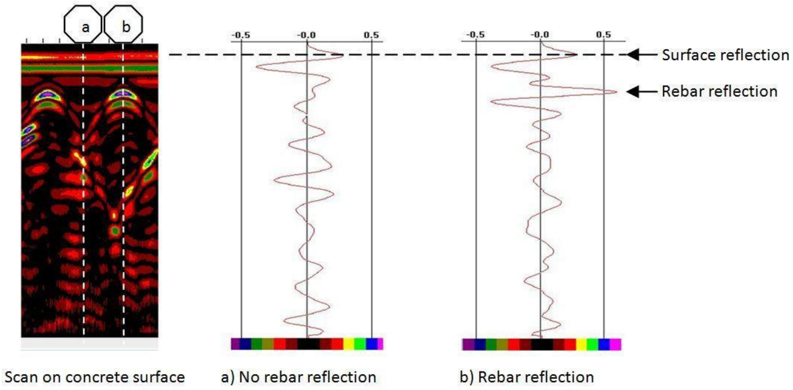

Figure 12: Example of a GPR scan. Scan location a) was performed at a location where no near surface rebar was present. Location b) is at the centre of a piece or rebar. Note the difference in the amplitude of signal for the same depth of the scans with and without the rebar.

The difference between the surface reflection and the reflection of the secondary positive peak of the reflection will be the two way time. Obtain the 2 way time for each of the locations where a direct measurement to the rebar was obtained. Plot the 2 way time(X) and the measured cover depth(Y) for each one of the locations. Perform a linear fit between all the points used for the correlation and obtain the linear equation that will establish a correlation between cover depth and 2 way travel time (Figure 13). Obtain the value of R^2. This value should be as close as 1.0 as possible in order for the correlation to be valid. An R^2 value of 0.98 and higher may be acceptable for rebar cover surveys and the operator should use his/her best judgment when applying this process.

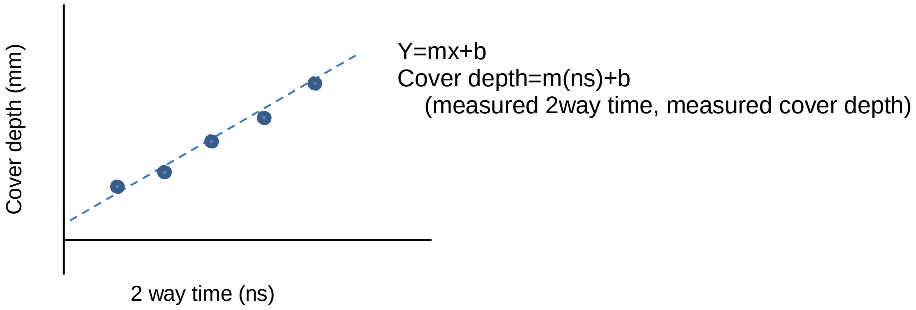

Figure 13: Correlation between cover depth and 2 way travel time. Linear fit and determination of the equation to be used in the survey.

Obtain the linear equation correlating the cover depth and 2 way travel time. After establishing this equation and an acceptable R^2 value, the equation will be employed to analyze the data obtained from the survey scans. Keeping the information organized and possibly in a table format is ideal. Create a table with the file name and the actual cover depth for all the locations. Having a table with additional notes for the general location of the scan and measurements within the structure may also be helpful. In case the operator and analyzer have questions regarding measurements the additional notes will help. Also these locations can be used as reference points when changing equipment or antennas.

F.7 ANALYSIS OF THE COVER DATA FILES

The operator will perform scans in the field. The scans will be documented in drawings and/or field notes with sufficient level of detail to be able to locate the scan location in the field. When scanning long distances the operator should take a physical measurement of the distance. In general, GPR systems are capable of recording distance information, however, because the distance measurements are generally performed with an encoder (survey wheel) cumulative error may exist over a long distance. Operators must be aware of the potential differences between the encoder measurement and the actual distance in the structures and apply the corresponding correction factors.

Once the scans have been performed, the files are downloaded to a computer where the operator can extract a spreadsheet with the 2 way travel time for each one of the files and their approximate location (distance) along the scan. In a spreadsheet apply the equation described in section 6.0 to the 2 way travel times to calculate the depth of cover.

F.8 EXAMPLE

A correlation example is presented in the following section. Five measurements were performed and their two way travel time was determined. Table 4 presents the two way travel times and the depth measurements.

Table 4: Two way travel times and corresponding direct cover measurements

Depth (mm)	File	Reflections (ns)		2 way time	Comments
		Surface	Steel	(ns)	
127	001	0.17	2.57	2.4	west wall, vertical bar-marked as location 1
93	002	0.17	2.01	1.84	west wall, horizontal bar-marked as location 2
65	003	0.17	1.46	1.29	column B-6, vertical bar -marked as location 3
39	004	0.17	0.92	0.75	shallower horizontal bar-marked as location 4
28	005	0.17	0.73	0.56	shallower bar vertical-marked as location 5

Note that the two way travel times are reported in ns. The difference between the surface reflection and the secondary positive peak of the rebar was selected for the calibration as noted in section 6.0. This operation was performed for each one of the test locations.

Figure 14 presents the correlation curve (linear fit) of the five points measured. The points were plotted in Microsoft Excel® and a linear fit line was included in the plot. The equation correlating the cover depth and the two way travel time was also obtained from Excel®.

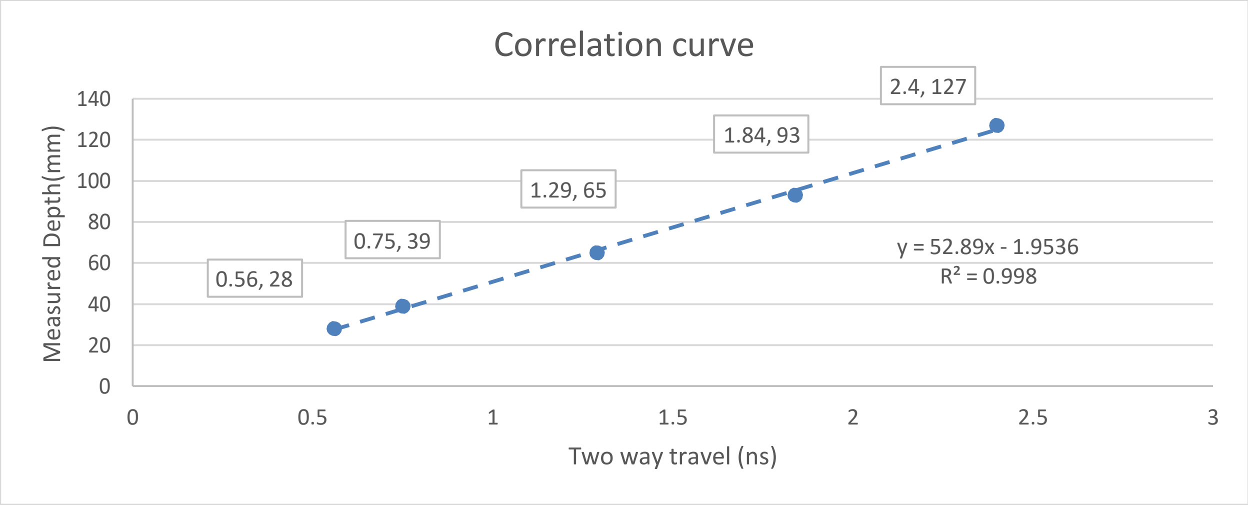

Figure 14: Plotted values of measured cover depth and two way travel times.

Figure 15 presents an image extracted from an actual scan in gray scale. The first red dot near the 0 ft. mark represents the surface reflection. The remaining red dots, at a deeper depth, are the selected pieces of rebar within the scan.

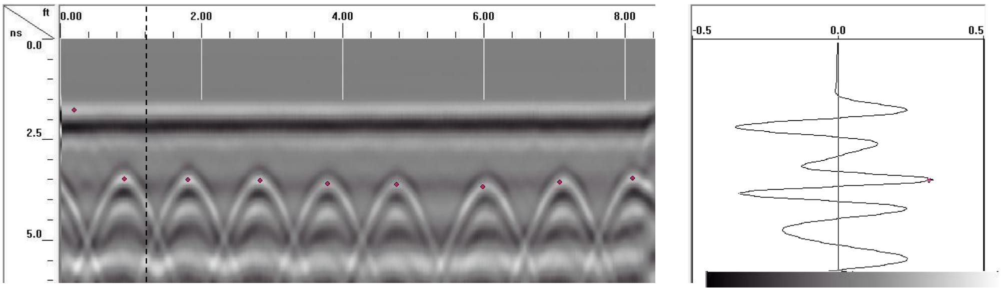

Figure 15: Surface and rebar reflections in GPR scan. Wiggle plot at the right hand side of the figure corresponds to the location of the first rebar (dotted line).

The wiggle plot presented on the right hand side of Figure 15, represents the wiggle at the location of the first piece of rebar. Note that the dot selected and the secondary positive peak are at the same approximate depth. The amplitude and polarity is colour coded for a simple visual interpretation. After selecting each of the pieces of rebar, the spreadsheet with the two way travel times and distances was extracted. Further, the two way travel time from the surface of the concrete to the rebar was calculated. Finally, the equation obtained from the correlation presented in Figure 14 was applied to determine the cover depth. The results are presented in Table 5.

Table 5: Summary of GPR scan results

Target	Dist.(ft)	Way Time (ns)	Two way time from surface (ns)	Calculated Cover* (mm)
Rebar	0.911	3.47	1.71	88
Rebar	1.811	3.49	1.73	90
Rebar	2.833	3.52	1.76	91
Rebar	3.789	3.59	1.83	95

Target	Dist.(ft)	Way Time (ns)	Two way time from surface (ns)	Calculated Cover* (mm)
Rebar	4.767	3.61	1.85	96
Rebar	5.989	3.66	1.9	99
Rebar	7.078	3.54	1.78	92
Rebar	8.111	3.45	1.69	87

Equation used for calculated cover

Surface reflection 1.76 ns

*y=[52.89(two way time from surface)] - 1.9536