Corrosion Prognostic Health Management Principles Applied to Deployment of Environmental Sensors on Australian Defence Force Helicopters

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ABSTRACT

There is a desire within the aircraft maintenance communities to move from the current inspection and repair methodologies for aircraft corrosion maintenance to a more proactive, evidence based, maintenance philosophy. Defence Science and Technology Group and BAE Systems Australia have been developing a capability for a Corrosion Prognostic Health Management (CPHM) system using a suite of tools that include environmental sensors, data acquisition hardware, corrosion prediction models and a Prognostic Health Management software platform. This paper describes the trial of environmental sensors to be deployed on the Tiger Armed Reconnaissance Helicopter and Multi Role Helicopter MRH-90 Taipan for the Australian Defence Force and compares the capability of the suite of tools in their current state with the requirements of a fully functioning CPHM system.

1.0 INTRODUCTION

The shift in corrosion maintenance philosophy away from 'find and grind' towards 'anticipate and manage' (Figure 1) was identified in the early 2000's [1]. The aim of this change was to allow fleet managers and maintenance organisations to reduce costs and increase availability of their aircraft. This can be achieved by reducing or eliminating inspections, decreasing time-based maintenance and optimising preventive maintenance (PM) actions by providing decision support. Lee et al. identifies the characteristics of a prognostic health management (PHM) system based on a transformation map of maintenance methodologies [2]. Well known maintenance methodologies and diagnostics techniques, such as PM, reliability centred maintenance and condition based maintenance (CBM) can be described based on the complexity and uncertainty within the system (Figure 1).

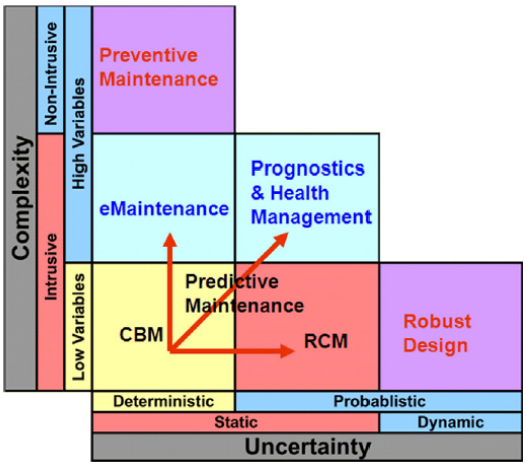


Figure 1: Transformation map of maintenance methodologies [2].

If the system includes condition indices that are deterministic such that the signal variables accurately indicate the current health of the system, CBM can be applied. This method relies on the development of a relationship model such that the data acquisition and processing results in actionable condition information. If the condition indices cannot be used with a relationship model to determine current health and remaining useful life, probabilistic models that utilise statistical tools such as failure modes and effects criticality analysis can allow reliability centred maintenance to optimise maintenance without providing an insight into the actual system performance. Complex systems involving larger numbers of variables linking to industrial business systems is the domain of e-maintenance. PHM is an evolved form of CBM where the CBM techniques provide input to prognostic models that assess current health status and predict future state based on a performance model. The complex nature of corrosion mechanisms and aircraft maintenance philosophies, as well as the uncertainty involved in predicting corrosion due to the variability in build quality between fleets of aircraft, point to PHM as the most applicable maintenance methodology within this domain.

Applied to airframe corrosion as a failure mechanism, CPHM measures the environment experienced at different locations and provides predictions of future corrosion states from environmental data (sensors) and operational data using a Prognostic Algorithm to inform maintenance decisions. The sensors measure environmental parameters identified in science based models as being critical to defining the corrosive environment: inhibitor depletion from primer, initiation of pitting and growth of corrosion. These sensors measure relative humidity (RH), air temperature (AT), surface temperature (ST) and time-of-wetness (TOW) at set time intervals. TOW has long been understood to control corrosion rates under atmospheric corrosion conditions [3]. Indirect estimations of TOW using ISO 9223 [4] fail to represent wetting phenomena such as condensation and deliquescence. Correlations between ISO 9223 defined TOW and atmospheric corrosion rates have been shown to be poor [5] and of little use in modelling the degradation of aerospace aluminium alloys. Schindelholz and Kelly [6] reviews both the wetting and drying phenomena associated with atmospheric corrosion and practical TOW measurement methods. Sets of metal electrodes separated by an insulating material have been used to estimate TOW by measuring the change in voltage, resistance or impedance that occurs as deposited moisture bridges the gap between electrodes. Sereda et al. [7] developed interdigitated circuits to form galvanic sensors that formed the basis for TOW estimation in ASTM G84-98 standard [8]. Resistance sensors using noble metal electrodes across which a DC or AC voltage is applied were used by groups in Australia for sensing atmospheric corrosion [9]. Commercial TOW sensor packages have been developed [10] using resistance sensors and using multiple sensor types in a single package (Luna Innovations Inc. developed a wireless miniaturized Smart Sensor Network for Aircraft Corrosion Monitoring).

Huynh et al. [11] examined systematic reviews of maintenance decision-making methods and concluded that most efforts have been focused on improving the quality of diagnosis leaving open the question of how to design and use the best condition indices for maintenance decision making. Indeed, in the area of CPHM, we have seen a similar trend of research concentrating on the improvement of sensors and corrosion modelling but little effort on real world implementation [2].

A commercial off the shelf sensing package developed by Luna Innovations Inc. [12] was used by the Netherlands Department of Defence to assess the severity of the operating environment of the NH90 helicopters by placing the LS2A sensor suite on a number of helicopters, as well as the ships they were embarked on, and at air bases where the helicopters were stationed [13]. The sensor suite contained a TOW, RH, ST and AT. They also used polarization measurements of an interdigitated aluminium electrode to determine a corrosion rate and cumulative mass loss. ‘t Hoen-Velterop [13] was able to show that salt loading and temperature played a large part in determining corrosion rate, and variation in conditions between missions were significant such that climatic data was not sufficient to assess the corrosivity of the embarked conditions. Based on hangar conditions, large reductions in corrosivity when the RH was below 50% were sufficient to extend the maintenance interval of 3 year saline inspection for helicopters that spent a significant period in storage.

BAE Systems Australia has developed a software tool to enable end-user interaction with a CPHM system. Environmental Degradation Monitoring and Prognostics (EDMAP) is a system that enables condition-based corrosion maintenance by providing a user interface to manage and process CPHM data inputs. EDMAP uses data from on-board sensors, off-board databases and corrosion prognostics to determine the current and future corrosion status of a platform. This status is referenced to maintenance opportunities to determine inspection deferrals and optimisation of maintenance planning. EDMAP is the equivalent to corrosion as Health and Usage Monitoring (HUMS) is to the management of aircraft fatigue. Together, the two systems aim to provide the end-user with information necessary to manage aircraft structural integrity. EDMAP can also bring clarity and rigour to special servicing activities, such as those based on saline or hot/humid exposure and wash/rinse scheduling by forecasting the need for these activities based on individual aircraft condition. EDMAP generates corrosion and environmental degradation reports within the software package, which are tailored to the specific needs of the maintainer. The logistics system for the global F-35 fleet employs EDMAP technologies for its CPHM capabilities.

Defence Science and Technology (DST) Group has adopted a corrosion modelling approach based on the deliquescence of salt(s) present on the surface and evidence that existing corrosion pits do not necessarily reinitiate when re-wetted [14]. Combining this with experimental determinations of the rate of formation of corrosion pits [15, 16] and the limiting cathodic corrosion current for individual alloys [17], a method to predict pitting corrosion has been developed [18]. Environmental sensors are used to record local AT, RH, ST and TOW. Time of Wetness is measured using an interdigitated galvanic sensor (Figure 2), originally developed by NAVAIR [19]. The galvanic current generated provides a measure of the surface area wetted out at any point in time [20].

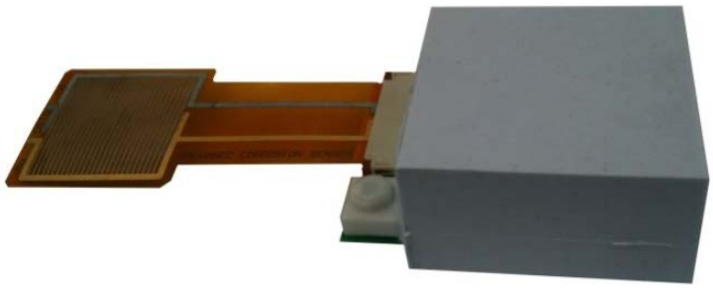


Figure 2: Data Logger with rubber potted body 40 mm × 52 mm × 22 mm.

Packets of wetness are analysed individually to calculate solution concentrations (NaCl, O_2) from known deliquescence constants of different salts. This system has been successfully trialled on a number of Australian Defence Force (ADF) platforms (Hawk 127 Lead-In-Fighter and Seahawk S-70B-2) [21].

Huynh et al. [11] proposes an approach to jointly quantify the performance and robustness of the CBM strategies that would be appropriate to the CPHM system detailed in this paper and assesses stress corrosion cracking as a failure mechanism using crack propagation following a time based model. As Huynh et al. were examining a system that did not include an active sensing element, it is necessary to modify the approach used in their paper to assess the operational effectiveness of the proposed CPHM system:

1. Develop a data collection strategy that supports diagnostic and prognostic requirements of the degradation and failure mode;
2. Develop a degradation and failure model for the considered system;
3. Synthesise diagnostic and prognostic condition indices on the basis of the degradation and failure model;
4. Build diagnosis and prognosis-based maintenance strategies and associated cost models;
5. Assess the performance and robustness of the considered strategies to find out reliable indices.

2.0 OPERATIONAL EFFECTIVENESS ANALYSIS

2.1 Data Collection Strategy

The degradation and failure models utilise environmental parameters to determine the depletion of the inhibitor as well as the initiation and growth of corrosion pits. These models are based on an atmospheric corrosion mechanism where deliquescence occurs as humidity rises in the presence of marine salts and requires RH, AT, ST and TOW as inputs. Many operational factors will influence the environment experienced by the helicopters. In addition to requiring access to operational information recorded through existing databases, helicopter storage (hangar) and preparation (flight line) environments as well as the timing of movements between these locations will support a prognostic capability by building a correlation between external and internal environments experienced by the helicopters.

2.1.1 Sensor Development

The degradation and failure model required RH, AT, ST and TOW inputs measured at set time intervals, termed the environmental data-stream. In addition to the modelling requirements, trial constraints require that the sensors be self-contained with data stored on-board for periodic retrieval using remote access.

The environmental sensors monitored by the data acquisition hardware are contained in a compact, ruggedized, wireless, battery operated, module called a Data Logger (DL) (Figure 2 and Figure 3). The

sensors incorporated comprise:

- Air Temperature (AT);
- Surface Temperature (ST);
- TOW; and RH.

The electronics comprise:

- lithium battery with an estimated 4 year life;
- low power microcontroller;
- non-volatile memory;
- real time clock;
- wireless 916 MHz transceiver; and
- trans-impedance logarithmic amplifier for the TOW sensor.

Outputs of the sensors are periodically recorded, typically half hourly, and stored in memory before being retrieved wirelessly by a Data Gathering Unit (Figure 3) at intervals spanning several months. The memory capacity currently allows approximately 170 days of logging.

Figure 3: Data Logger (un-potted - left); Data Gathering Unit (centre); and witness plates and TOW sensor installed in an aircraft (right).

The Data Gathering Unit can wirelessly download the contents of a DL memory from up to 10 m away at 19.2 baud. The data is stored as a text file by the Data Gathering Unit and uploaded to a USB memory stick. The DL is housed in a small custom bracket designed in consultation with aircraft operators. It is attached by adhesively bonding to the airframe. A thermally conductive paste is used to provide good thermal contact with the ST sensor. The enclosure also provides a location for placement of Witness Plates (WP) and an opening to inspect the serial number (Figure 3).

The TOW sensor, developed by DST Group from a previous NAVAIR design, comprises interdigitated cadmium and gold tracks on a flexible polyimide film [19, 22]. This sensor measures the current produced when moisture is present on the surface of the sensor. This measurement has been shown to be proportional to the surface coverage of NaCl in a range of environments (Figure 4).

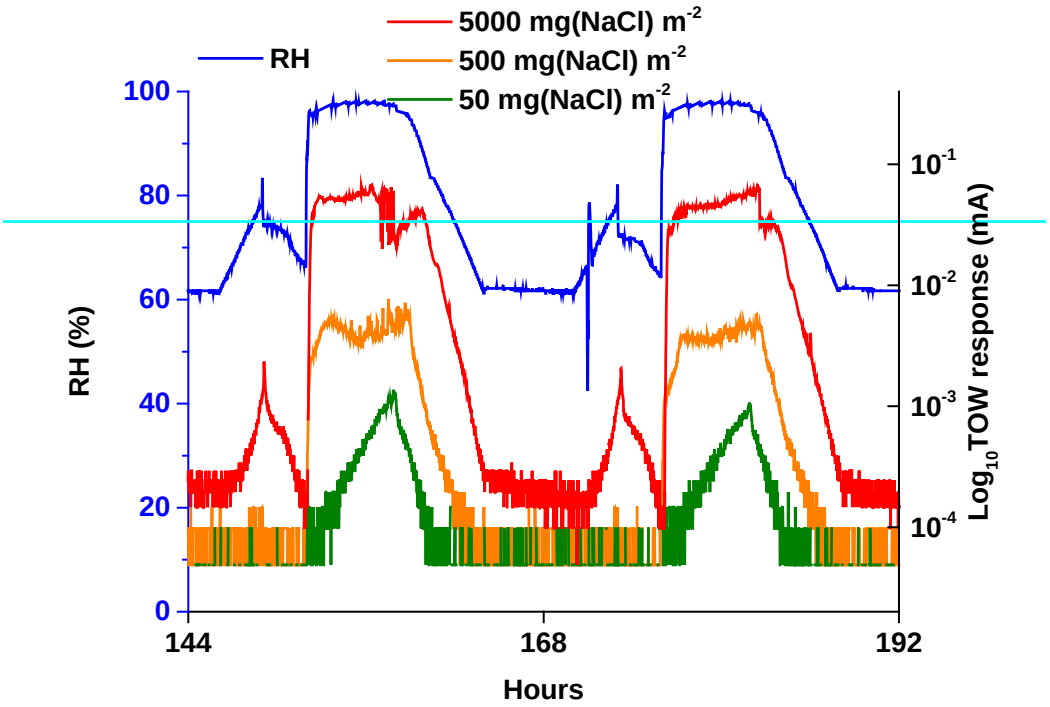
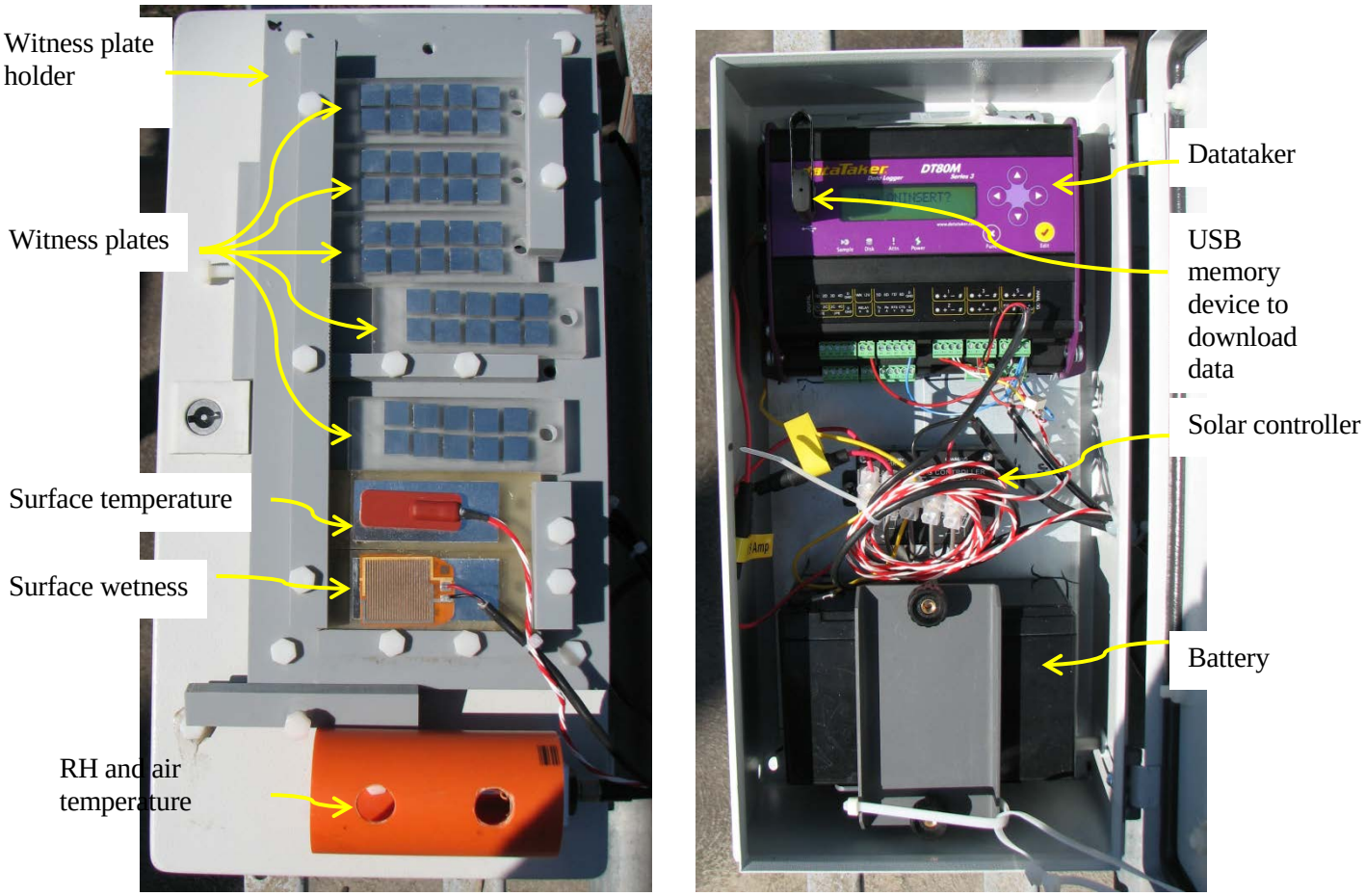


Figure 4: Response of TOW sensor to different levels of NaCl contamination; (a) 50 mg m^{-2}; (b) 500 mg m^{-2}; (c) 5000 mg m^{-2} (horizontal line corresponds to 75% RH, the level at which NaCl deliquesces).

2.1.2 Ground Based Stations

The program includes a series of ground-based stations (GBS) installed at relevant geographical locations. These GBS allow for regular collection of environmental data from a given location and corresponding corrosion data for relevant alloys via exposure of WPs adjacent to the sensors [18]. Validation of the environmental and corrosion models will be performed throughout the program using data gathered from the GBS. Unlike the on-board sensors, where there is little opportunity to collect corrosion measurements during the program, the GBS provide an on-going source of corrosion measurements from alloys exposed in representative environments.

A standardised, modular design has been developed for the GBS which allows deployment of a number of WPs and a suite of sensors at the same location (Figure 5). Except for the TOW sensor all components are commercial off the shelf. The GBS are self-contained, using an internal battery for power. Where possible a solar panel is deployed to maintain battery charge. Mains power can be used, but issues with maintaining connection mean that an exchangeable high-capacity alkaline battery is preferred when solar charging is not possible.



(a) (b)

Figure 5: Ground Based Station: (a) External layout showing WP Holder with WPs and sensors; (b) Internal layout showing data acquisition and power system.

At present data is retrieved along with two WPs every 3 months. At the end of each year a complete new set of WPs is deployed. The TOW sensor is 'reset' at the same time by rinsing with distilled water to maintain the salt loading synchronised with that present on the surface of the WP. By this schedule the build-up of salt can be tracked throughout the year and its effect on corrosion of the exposed aluminium surfaces measured.

The GBS are designed to be maintained by local personnel using an 'exchange pack' provided by DST Group. This means regular retrieval of data and recovery of WP is possible with the GBS. Remote monitoring via a 3G data link is possible, but requires more power and may not be suitable for locations where stray transmissions need to be minimised. While WP are deployed remote monitoring provides no advantage, but when GBS are used only for monitoring (i.e. no WP deployed) it will reduce the need for local personnel to attend.

2.1.3 On Board Deployment

Locations of interest on the Armed Reconnaissance Helicopter (ARH) were determined by the aircraft maintainers and holders of approved engineering organisation using the following criteria:

"The CPHM_Installation shall have a CPHM fitted to a minimum of four (QTY: 4) different locations, on the ARH Tiger, which have equipment that would lead to one or more of the following events, if the equipment was corroded to an unserviceable condition:

A. Safety Critical Event.
B. An event that leads to significant financial cost due to aircraft unserviceability."

For each item on the ARH that could lead to the given event, a corrosion vulnerability score was calculated. Components of interest were categorised by zones on the aircraft. The components of interest were identified as safety critical equipment and any metallic support structure and structural items identified in the structural repair manual. Each component was assessed with regard to its criticality (Table 1), inspection frequency (Table 2) and environmental exposure (Table 3). The product of these results determined the Vulnerability score.

Vulnerability Score = [Criticality Score]*[Inspection Frequency Score]*[Environmental Exposure Score]

Table 1: Criticality weighting for vulnerability score calculation.

Criticality score: Biased on how critical that sub-system or component is to the ARH system. It reflects the level of impact the item has on the aircraft's serviceability and how significant the financial costs will be should the component require repair or replacement due to corrosion.	
Safety Critical Items, Structurally significant items	10
Primary or Important parts	4
Secondary parts	1

Table 2: Inspection frequency weighting for vulnerability score calculation.

Inspection Frequency Score: Biased for components that are not routinely inspected; the results from the CPHM in such a location can then be used to identify if inspection intervals in that location should occur.	
Components in zones that are inspected every 1200 Flying Hours (FH) or 6 years	1.5
Components in zones that are inspected every 800 FH or 4 years	1
Components in zones that are inspected every 400 FH or 2 years	0.5

Table 3: Environmental exposure weighting for vulnerability score calculation.

Environmental Exposure Score: Broadly reflects how exposed the component is to corrosive elements that can affect the ARH such as precipitation, salt spray and dust. This score is therefore biased for how likely a component is to corrode.	
Components in zones that are exposed to the corrosive elements from the atmosphere	1.5
Components in zones which are exposed to corrosive elements from the atmosphere when barriers are routinely removed, such as maintenance bay doors and cockpit doors	1
Components in zones that have a barrier preventing the ingress of corrosive elements from the atmosphere and the barrier is not typically removed	0.5

Each zone was assessed to determine its vulnerability score and zones for which a corrosion rectification program (stub wings) was in place, or with similar characteristics to zones higher up on the vulnerability score (engine zone), removed. The five locations (Figure 6) deemed to have the most severe consequences to system safety or aircraft serviceability that could occur due to corrosion were:

a. Within the Main Gear Box (zone 4500)
b. Within the Cockpit (zone 2100 and 2200)
c. In the Aft Section (zone 3200)
d. Between Frame 2 and 3 (zone 1200)
e. Between Frame 1 and 2 (zone 1100)

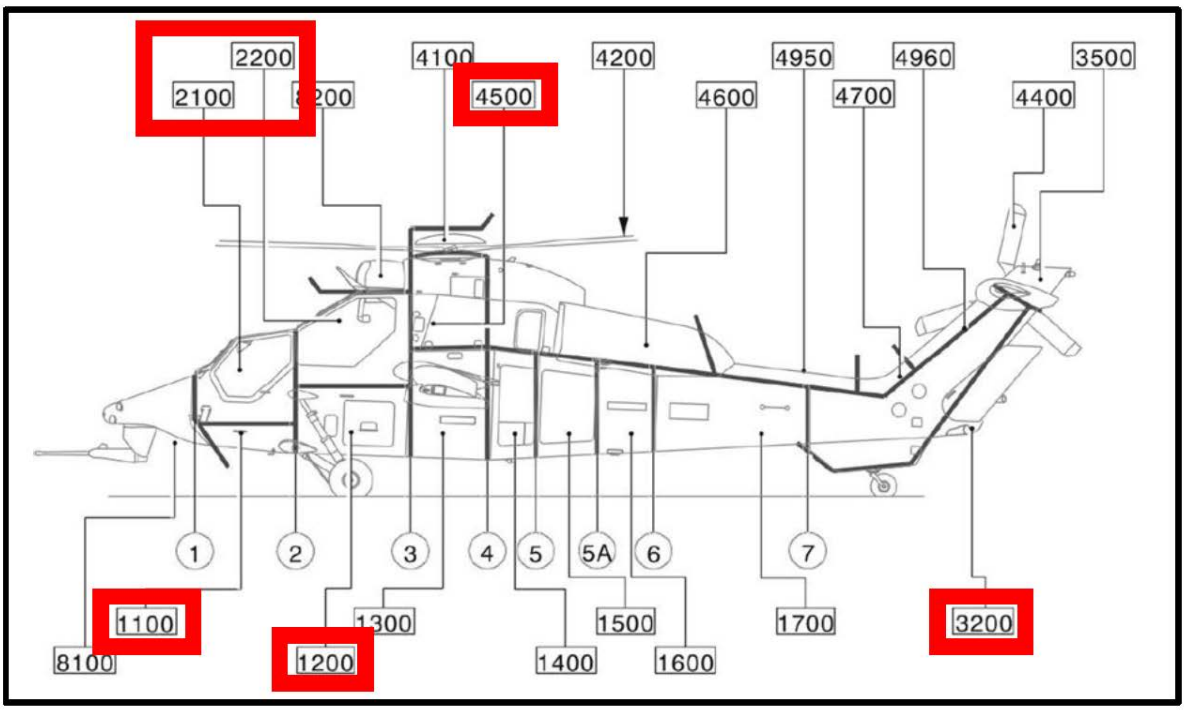


Figure 6: Maintenance zones for the ARH helicopter chosen for DL deployment.

Following a critical design review, a Special Technical Instruction (STI) and Engineering Report were released by the approved engineering organisation, for the installation of the DL's to the ARH and corrosivity data retrieval. An important function of the STI is that it incorporates the data retrieval from the DL's of each aircraft included in the maintenance activities. The STI has several functions and is the engineering document that describes all facets of the installation, management and removal of the CPHM data loggers on the ARH. The main activities include:

(i) Identifying the eight ARH aircraft tail numbers that will be fitted with the five DLs
(ii) Identifies all the elements of the assembly including the DL, WPs, and mounting bracket
(iii) Instruction on the method and materials used to mount and fit the DLs
(iv) Instructions on the Data Gathering Unit, the method for downloading and returning the collected data
(v) Instructions on the method used to remove the DLs and restore the location.

2.2 Witness Plate Development

Witness plates are deployed alongside the sensor system, both GBS and DL, to provide a means to validate the degradation and failure models. Each WP contains a number of coupons of alloys relevant to ADF platforms. Figure 7 shows a typical WP with three pairs of coupons. Both coupons in each pair are the same alloy. The size of the WP and number of coupons can be varied to accommodate different applications. In the case of the ARH deployment, a three by two arrangement of coupons was used due to the size constraint imposed by the DL bracket to which the WP was bonded. The alloys used were AA2024-T351, AA7050-T7451 and AA7075-T651 For the GBS, an additional two alloys were included, AA2124-T851 and AA7085-T7452.

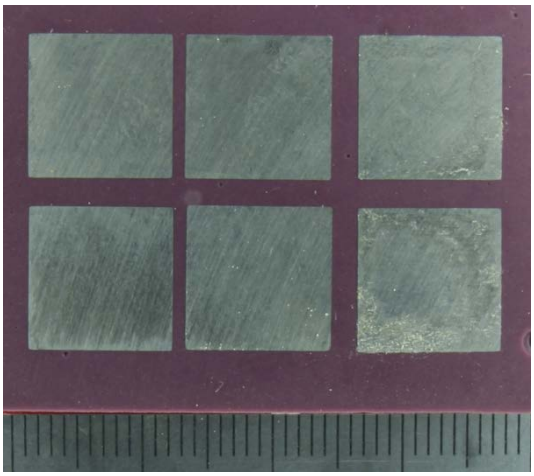


Figure 7: Witness plate.

The WPs are designed to provide a consistent surface finish and to be easily analysed at the end of a test. Analysis of any corrosion damage present on the alloy coupons after exposure is carried out by white-light interferometry using a Bruker GTK surface profiler. This allows consistent, repeatable analysis of large numbers of coupons. The instrument measures the surface topography of each alloy coupon and extracts the dimensions and volume of every corrosion pit on the surface. This data is stored as a text file for comparison with predictions of corrosion using the environmental data gathered from the sensor suite.

2.2.1 Operational Data

The sensors produce environmental data outputs that are used to characterise the environment that the aircraft has experienced, for input to the CPHM system software. To support the CPHM models in undertaking diagnostic and prognostic analysis of the condition and future condition of the aircraft structure, operational data on the aircraft is required. This operational data consists of flight and mission information system outputs from the aircraft systems and flight crew logs to characterise the physical aspects of the aircraft operations. The flight and mission information system data includes:

(i) aircraft tail number;
(ii) date;
(iii) start location;
(iv) operation number;
(v) mission ID, type and duration/times;
(vi) take-off time;
(vii) landing time;
(viii) number of landings (by type and environment): and
(ix) mission code(s) (for the respective flight), (These include "Hover corrosive, Hover erosive, Hover passive, Hover very corrosive, Run on corrosive, Run on erosive, Run on passive, Run on very corrosive", etc.).

During embarkation on board ship, additional operational data is gathered from the ship's meteorological station and log to provide:

(i) air temperature;
(ii) ambient RH;
(iii) wind speed and direction;
(iv) ship location; and
(v) aircraft location (deck or hangared).

The operational data is utilised to describe the physical environment that the aircraft was operated in and the prognostic modelling analysis can describe the level of corrosivity experience and have an impact on the aircraft maintenance.

2.3 Degradation and Failure Model

2.3.1 Environmental Model

The Environmental Model uses sensor data collected to estimate periods of wetness. Periods of wetness are used by the Inhibitor Depletion Model (IDM) to estimate the extent of inhibitor leaching and the Pitting Corrosion Model (PCM) to estimate the probability of pitting and pit growth for a given alloy.

2.3.2 Inhibitor Depletion Model

The Inhibitor Depletion Model uses inputs from the Environmental Model to estimate the extent to which the aircraft's protective coating has been depleted by regular leaching events. Corrosion inhibiting species from protective aircraft primers will leach into surface moisture to protect the underlying metal from corrosion. However, over time, the primer adjacent to a corrosion site will be depleted of inhibitor and the likelihood of pitting will increase as protection is lost. The Inhibitor Depletion Model estimates inhibitor leaching kinetics and the subsequent state of protection for each wetness period.

2.3.3 Pitting Corrosion Model

The outputs of the environmental model are extracted and the characteristics of the electrolyte are determined. A droplet will form at the appropriate deliquescence RH of surface salts and form individual electrochemical corrosion cells.

The PCM estimates a likely pit formation and potential size. Populations of corrosion pits are created when aluminium surfaces are atmospherically wet, as determined by the Environmental Model. When wetness occurs an individual pit can initiate and propagate before terminating when the surface dries. These pits do not grow further during subsequent periods of wetness [14]. The growth of pits on the aluminium surface

under droplets is calculated using cathodically-limited kinetics [18].

The PCM produces a distribution of likely pitting corrosion on a given alloy for the relevant period. The outputs of the PCM will be used to develop condition indices based on predicted corrosion levels

2.3.4 Prognostic Algorithm

A Prognostic Algorithm (PA) brings together the individual degradation and failure models for converting sensor data into an environment and using this as an input for the inhibitor and pitting corrosion models to estimate the corrosion condition indices and provide an output in terms of a corrosion state. The Prognostic Algorithm can also use predicted data to estimate the future corrosion state. Inputs from the GBS program are intended to provide information on the effect of different base locations and operational scenarios to develop predictive data sets and condition indices that relate directly to the amount of corrosion maintenance predicted at different locations on the aircraft.

2.4 Corrosion Index Prediction - CPHM Architecture

The CPHM system must be capable of synthesising the diagnostic and prognostic condition indices on the basis of the degradation and failure model. The trial will demonstrate the capability of the CPHM system to capture and store data from multiple sources, automate data verification, execute the model using acquired data, and provide outputs that can aid operator decision-making.

A CPHM architecture (Figure 8) was developed for use on the ARH, with the degradation and failure models described above contained within the EDMAP software package developed by BAE Systems Australia.

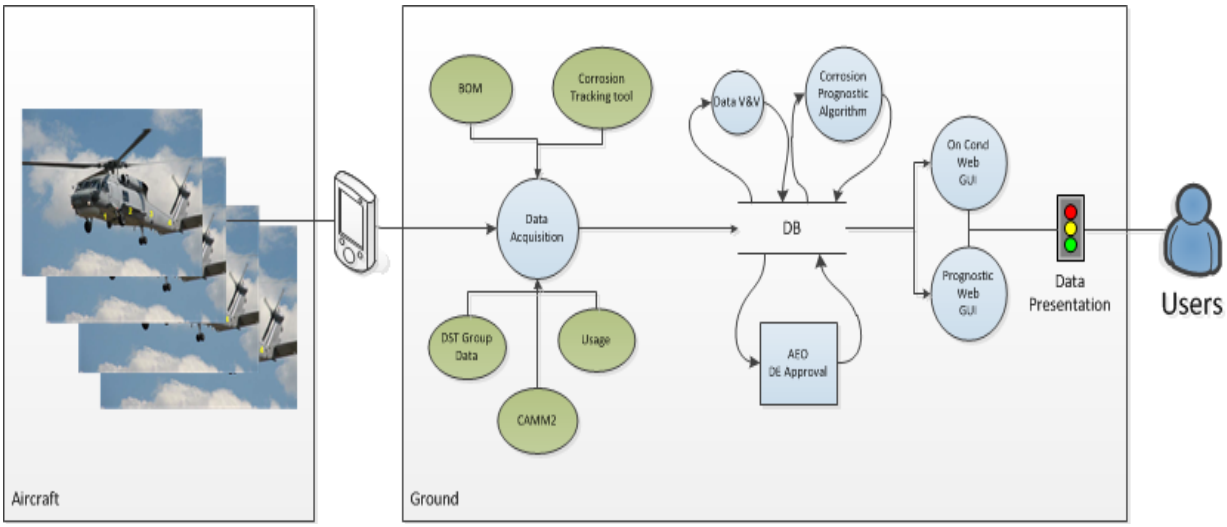


Figure 8: A CPHM architecture.

2.5 Maintenance Strategies and Cost Models

In their review of maintenance decision-making methods Huynh et al. [11] concluded that most efforts have been focused on improving the quality of diagnosis leaving open the question of how to design and use the best condition indices for maintenance decision making. One of the largest barriers to implementing a decision making framework for aircraft maintenance is the quality and fidelity of the maintenance data that

would provide the basis of any cost model. The maintenance zones for the ARH were classified as inspected every 400 FH (two years), 800 FH (four years), or 1200 FH (six years). With corrosion treated as an event based mechanism, it is only after significant time periods that any correlation between the measured environment and any resulting corrosion can be examined. This results in the need for an iterative development cycle for a CPHM system. Boyd [23] developed a four stage iterative decision making process that Holmes et al. used in describing military aerospace sustainment [24]. Boyd's OODA loop (Figure 9), an acronym for the four stages of decision making Observe, Orient, Decide and Act can be applied to CPHM development.

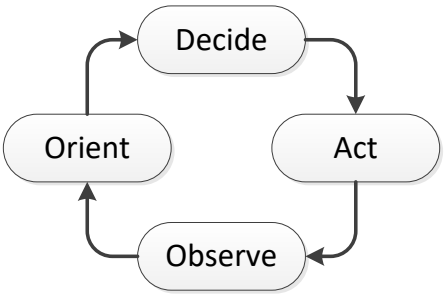


Figure 9: The simplified OODA loop [23].

The environmental data collection forms the 'observe' stage where information is gathered about the system, we 'orient' when we analyse the data, then 'decide' what changes to the system are needed and 'act' with deployment of a new system. This cycle has concentrated on iterative improvement of sensor design and prognosis with the current deployment the third in a series of deployments. Table 4 below shows the iterative development of the CPHM System across the three cycles.

Table 4: Iterative Development of CPHM System.

OODA	Deployment		
	Hawk Lead-In-Fighter	Seahawk	ARH
Observe	Sensor trade study 2 locations on 4 aircraft 2 GBS	4 locations, deployment on two aircraft Input into a CPHM architecture	Targeted locations on eight aircraft 2 GBS at deployment locations Live use of a CPHM architecture
Orient	Confirm link between models and WPs Laboratory validation of TOW response	Confirm wireless Include inhibitor depletion model	Reporting of data integrity Condition indices comparison to maintenance data
Decide	Down select of sensors	Data integrity mechanism Link to maintenance data Validation of TOW response in degradation and failure models	Future
Act	Development of prognostic models	Develop CPHM architecture to include reporting Wireless retrieval of Data	Future Extend deployment across longer timeframe Integrate into maintenance practices

3.0 ASSESSMENT

An initial deployment of environmental monitors was undertaken on the Hawk Lead-in-Fighter for the ADF [21]. This deployment consisted of two locations on four aircraft. The second deployment on the Seahawk S-70B-2 helicopter was extended to involve the placement of sensors in multiple locations, extended to incorporate the inhibitor depletion model, and WPs for model validation. The third trial on the ARH is extended even further with the incorporation of sensors in more locations and greater number of aircraft to represent the fleet. The big data load will have integrity verified and integration and analysis by the diagnostic and prognostic software. Progression of the aircraft trials has occurred over the three iterations.

4.0 CONCLUSIONS

The CPHM system being evaluated will enable collection of environmental data targeted to support validation and refinement of extant corrosion models while demonstrating the feasibility of such a system on a fleet of aircraft that experiences a wide range of operational environments. Information gained will be used to optimise specific PM tasks providing immediate benefit to the aircraft operators. The program will also result in collection of environmental data across a full maintenance cycle for individual aircraft. This will enable a correlation between the corrective maintenance for individual aircraft and development of a prognostic capability quantifying the corrosivity across the full range of operational environments experienced.

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