Corrosion Sensors to Reduce Aircraft Maintenance

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ABSTRACT

There is an increasing trend for aircraft operators to address through-life issues and attempt to reduce the operational costs of support. Corrosion is an important consideration here since it can lead to material loss and is often the precursor of fatigue cracking. Whilst these are issues for ageing aircraft that might be kept in service well beyond their original design life there is also a move to make new airframes less costly to support and operate. The ability to monitor and predict the corrosion or remaining corrosion life in an airframe would have a major impact on the cost of through-life support. Corrosion sensors have often been proposed for monitoring the degradation of civil and military airframes. There are many types of possible sensors and several different approaches to using them. The maturity of the technology of each type of sensor is different. This leads to the consideration of near term and future system options. In this paper, two methodologies based on corrosion sensors and the combined use of sensors and predictive modelling are proposed, based mainly on sensors designed and fabricated at BAE Systems. Corrosion sensor designs and results from laboratory and field trials are presented along with a discussion on how corrosion sensors might be deployed for operational benefit.

1.0 INTRODUCTION

There is an increasing trend for aircraft operators to address through-life issues and attempt to reduce the operational costs of support and improve aircraft availability. Corrosion is an important consideration here since it can lead to material loss and is often the precursor of fatigue cracking. Whilst these are issues for ageing aircraft that might be kept in service well beyond their original design life there is also a move to make new airframes less costly to support and operate.

Corrosion sensors have often been proposed for monitoring the degradation of civil and military airframes. There are many types of possible sensors and several different approaches to using them but there is little information available that allows sensor outputs to be simply related to the state of the surrounding structure. Sensors for corrosion and perhaps other forms of environmentally-induced degradation can only be used for managing and supporting aircraft in service if there is a way to interpret the sensor information into an easily understood message of what actions, if any, are required for the maintenance support engineers.

With the trend for customers to force the risks associated with operational service onto the supplier, reliable quantitative information that describes corrosion and other degradation may well be useful. Such quantitative information can also be used to support estimates of residual value if assets need to be moved on. In addition, legislation will force operators and manufacturers to use new corrosion protection schemes such as non-chromate treatments and paints that may perform differently to their “traditional” predecessors. Michelin (2003) [1] has described some of the requirements of chromate-free primers and Kinzie (2003) [2] discusses the cost of corrosion for military aircraft which, for the USAF, exceeded $1B in 2001 with some aircraft types costing more than $200, 000 per year per airframe in direct corrosion costs.

2.0 THE PROCESS OF ENVIRONMENTAL DEGRADATION

A typical aerospace structure is commonly fabricated from aerospace qualified aluminium alloys with metal fasteners. The structure is generally protected from the elements by treating the aluminium surface through anodising or conversion coating with a chromate containing primer overlaying the surface. Finally a top coat is applied. Around the fasteners and fastener holes there is often applied a high quality sealant. It is generally hoped that the protective surface is perfectly flawless but on a large structure undergoing the rigours of everyday service this cannot be the case. Impact damage, in flight, during landing and take - off or on the ground is a common occurrence. Damage during maintenance (tools and spilt fluids) can occur as well as paint cracking at high stress points around joints and at fasteners. Paint can also crack due to high thermal cycles and fatigue [3, 4]. The progress of the degradation of the structure from operational degradation is illustrated in Figure 1. A typical flaw structure is shown in Figure 2.

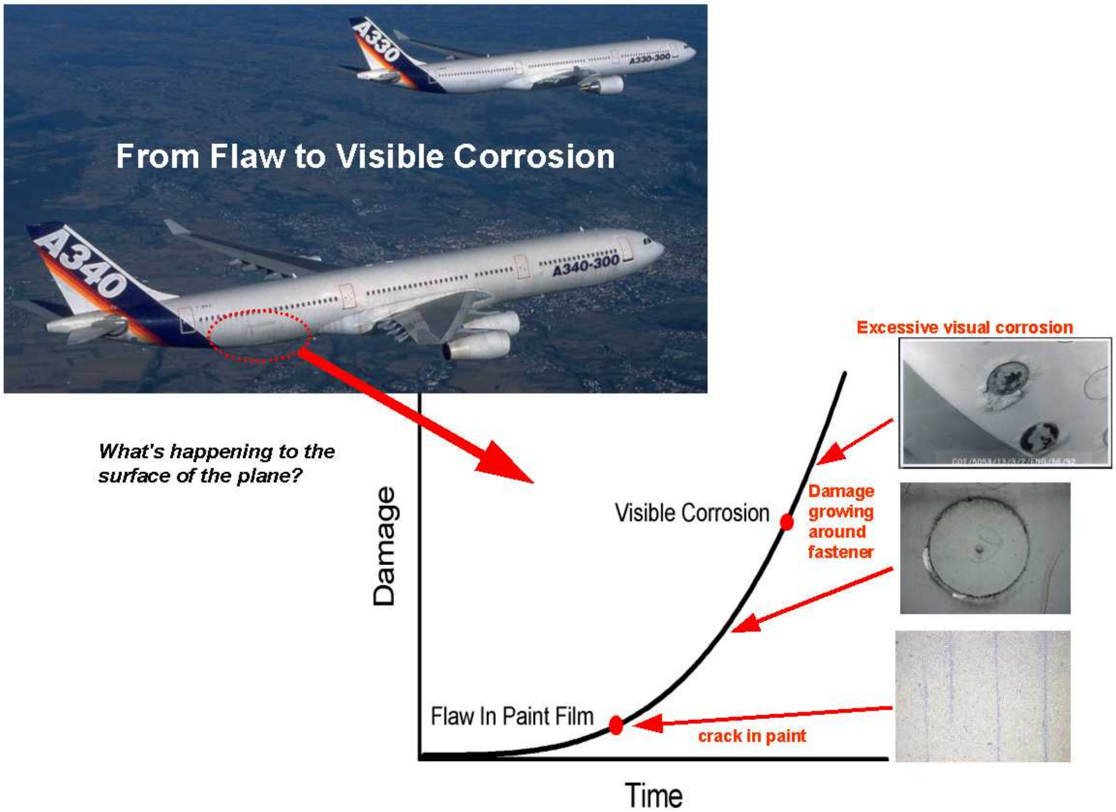

Figure 1: Progress of degradation in a protection scheme.

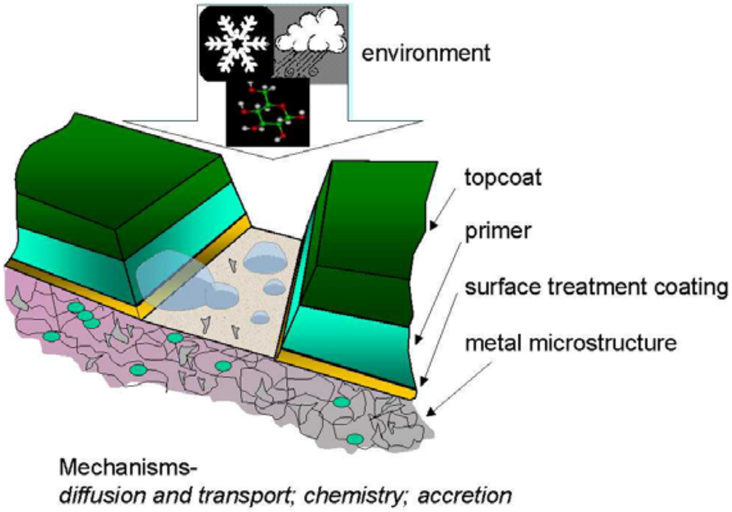

Figure 2: Structure of a flaw in a standard protection scheme illustrating environmental factors in chromate exhaustion and metal degradation.

3.0 GENERAL APPROACHES TO CORROSION SENSING

Corrosion sensors are not new but they have mainly been applied to large fixed installations such as pipelines and offshore structures. These applications are not usually weight-sensitive and much of the sensor technology has not been directed towards aerospace needs in terms of low mass, operating conditions, sensitivity and materials. In recent years, however, the potential benefits of corrosion monitoring, often as part of a larger strategy on corrosion management, have generated a substantial body of research for aircraft use. Additionally, changes in the business environment and advances in fabrication methods and datalogging have now made aircraft corrosion sensors a viable technology that is being closely examined.

There are four basic approaches to corrosion monitoring using discrete sensors: direct measurement of corrosion effects, measurement of corrosivity by relating the degradation of the sensor itself to the degradation of an adjacent structure, measurement of corrosion products and measurement of climate (or microclimate) to input into a predictive model. These are described briefly below.

3.1 Direct Measurement of Corrosion Effects

It is possible to measure corrosion effects directly using electrochemical sensors such as EIS (Electrochemical Impedance Spectroscopy) or MEMS-based sensors that have been postulated. This approach may be suitable for monitoring localised areas but is unlikely to offer large area coverage without using many sensors. Another approach would be to use corrosion-indicating paints whose optical signature changes when the pH of the underlying structure changes due to corrosion.

3.2 Measurement of Corrosivity of Environment

The term *corrosivity sensors* can be used to describe several types of sensor whose response to corrosive conditions may be correlated to the corrosion of an underlying structure. For example, galvanic sensors might indicate time of wetness or the corrosion of metallic elements in a sensor can be monitored via their change in electric resistance. The output of corrosivity sensors needs to be related to the underlying structure by calibration, and it is this aspect, especially when dealing with complex painted structures, that needs careful attention. Some corrosivity sensors can incorporate analogues of the underlying structure and can also be painted and treated in the same way as the structure so that their response to the environment and contaminants is similar to that of the structure they are monitoring.

3.3 Measurement of Climate (or Microclimate) to Input into a Predictive Model

For general in-service degradation based on the environmental and service history of the aircraft it is possible to construct an entirely non-invasive model to predict the onset and progress of corrosion. To overcome the difficulties of modelling pollution accretion, UV damage, and unexpected atmospheric circumstances a predictive model could be supplied with data from environmental sensors which measure the climate or microclimate of a components or group of components. Unfortunately, the modelling and sensor technologies are not yet ready for operational deployment on aircraft.

3.4 Measurement of Corrosion Products

Chemical sensors can indicate the presence of specific ions that would arise from a corroding structure. These could be located in bilges or in locations where corrosion products might accumulate and would therefore, in effect, be able to indirectly monitor large areas. To date, however, such sensors cannot demonstrate stable longevity or resistance to poisoning by contaminants. Some corrosion indicating paints can also change their fluorescent properties when they react with certain corrosion products.

4.0 TYPES OF SENSOR

Categories of corrosion sensors are listed in Table 1. The various stages of corrosion and the availability of sensors to detect the physical phenomena associated with each stage are illustrated in Figure 3.

Table 1: Several types of corrosion sensor, principally aimed at aircraft structures.

SENSOR TYPE	COMMENT
Corrosion Coupons	Corrosion rate is determined by weight-loss measurements. Coupons can be used as witness plates for calibrating other sensors.
Electrical Resistance	The resistance of a metallic track is measured. Loss of metal due to corrosion changes the electrical resistance.
Galvanic	The galvanic current or voltage generated by separated electrodes made of dissimilar metals can be used to measure the presence of a conducting, and hence corrosive, environment.
Electrochemical Impedance Spectroscopy (EIS)	Electrochemical Impedance Spectroscopy (EIS) can be used to assess the degradation of coatings. Portable systems are available. Also, it may be possible to embed electrodes beneath the coating. Such systems model the coating, substrate and electrolyte as elements in an AC circuit. The resistance and capacitance of each circuit element is inferred from observations of changes in impedance with the frequency of a small applied potential. The inferred values indicate the state of the coating.

SENSOR TYPE	COMMENT
Electrochemical Noise (EN)	Electrochemical Noise (EN) sensors measure the rapid fluctuations in corrosion current and voltage between electrodes. Corrosion potential fluctuations can indicate the onset of events such as pitting, exfoliation, and stress corrosion cracking (SCC).
Acoustic Emission (AE)	Laboratory tests indicate that Acoustic Emission (AE) can be used to monitor the propagation of corrosion and stress corrosion cracking.
Chemical sensors	Chemical sensors measure corrosive chemical species or corrosion products. There are many different technologies, including Ion Selective Electrodes (ISEs), Ion-Selective Field Effect Transistors (ISFETS), and optical sensors (see below). Lack of long term stability and vulnerability to poisoning may be issues.
Corrosion-Indicating Paint	Corrosion-indicating paints are under development. The paint responds to chemical changes associated with corrosion by changing colour or fluorescence. Examples of relevant chemical changes are, change in pH; oxidation, and complexing with metal cations.
pH sensors	ISE-based pH sensors are likely to be the best technology but the issue of long-term calibrated performance remains.
Biological sensors	Biologically-induced corrosion, or “biocorrosion”, can be monitored using electrochemical sensors. In general, biosensors have limited lifetimes and at present are unsuitable for long term exposure.
MEMS-based sensors	Micro-Electromechanical (MEMS) devices are usually fabricated in silicon and have been proposed for corrosion sensors. Micro-cantilever systems whose vibration characteristics change according to the mass of the beam can form the basis of a range of sensors.
Ultrasonic	Active ultrasonic sensors comparable to those currently used in NDE can measure thickness loss directly under a sensing head. Guided ultrasonic waves that propagate along surfaces and interfaces might detect corrosion over larger areas. SAW (Surface Acoustic Wave) devices are in theory much more sensitive.
Optical sensors	An optical fibre with Bragg gratings can be coated with an electrochemically active species that changes colour as a result of the corrosion reaction. These sensors can be embedded in sealant and can monitor long lengths of structure. Lack of long term stability and vulnerability to poisoning may be issues.

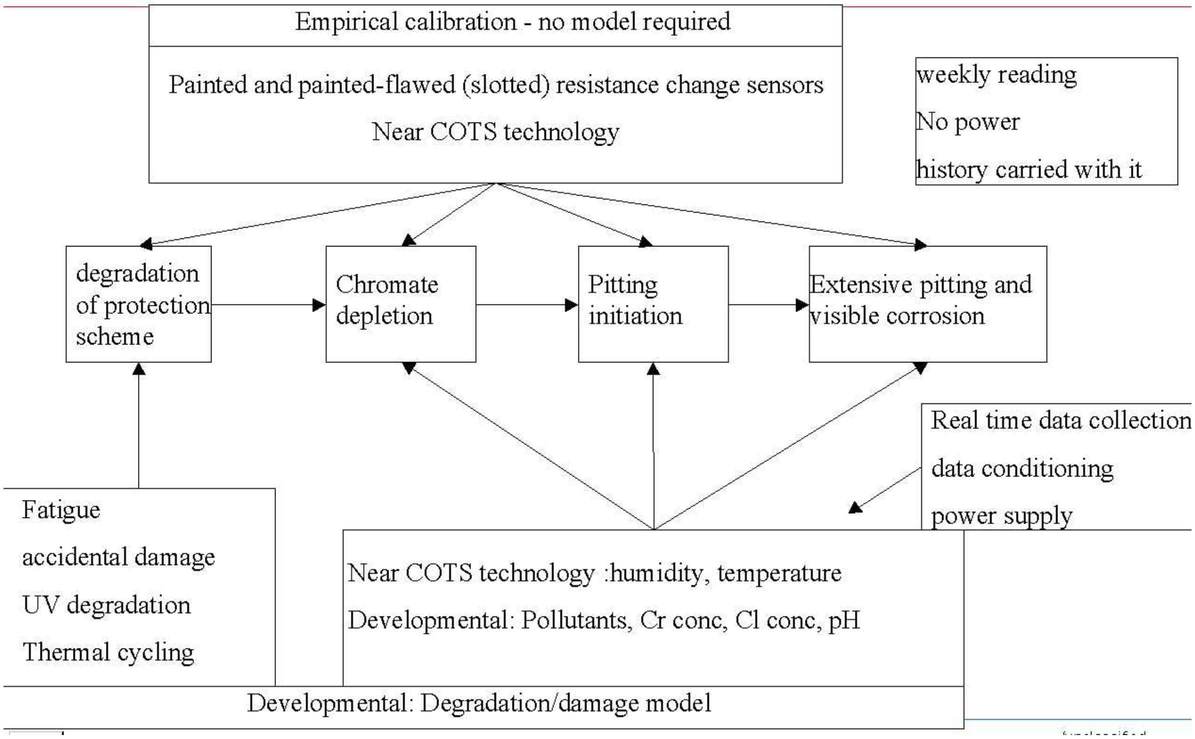

Figure 3: The various stages of corrosion and the availability of sensors to detect the associated physical phenomena.

Corrosion sensor systems and corrosion modelling are emerging technologies. In the short term, simple, passive sensor systems are achievable. These require no continuous power or real time datalogging, carry their history of degradation with them, and react almost exactly as the surrounding structure would react. Such systems are currently being flight tested. They could be used for usage monitoring, i.e. to provide a record of the environments experienced to date. They could also be used as an inspection surrogate, such that degradation of a sensor would indicate that comparable degradation had occurred in an inaccessible component. Both functions could help in minimising the need for inspection and the associated downtime.

An example of a simple, unpowered, passive system is the BAE Systems Sentinel (Figure 4). This indicates the breakdown of the protection scheme, the onset of corrosion, and the progress of corrosion. The degradation rate is measured using a multimeter or by existing onboard systems. No additional instrumentation is necessary. There is no requirement for additional software, modelling, or maintenance activities to handle data or change batteries. The result is in the single reading. Sentinel has been installed on the Tornado aircraft and various land-based assets, and has been selected for the F-35 JSF.

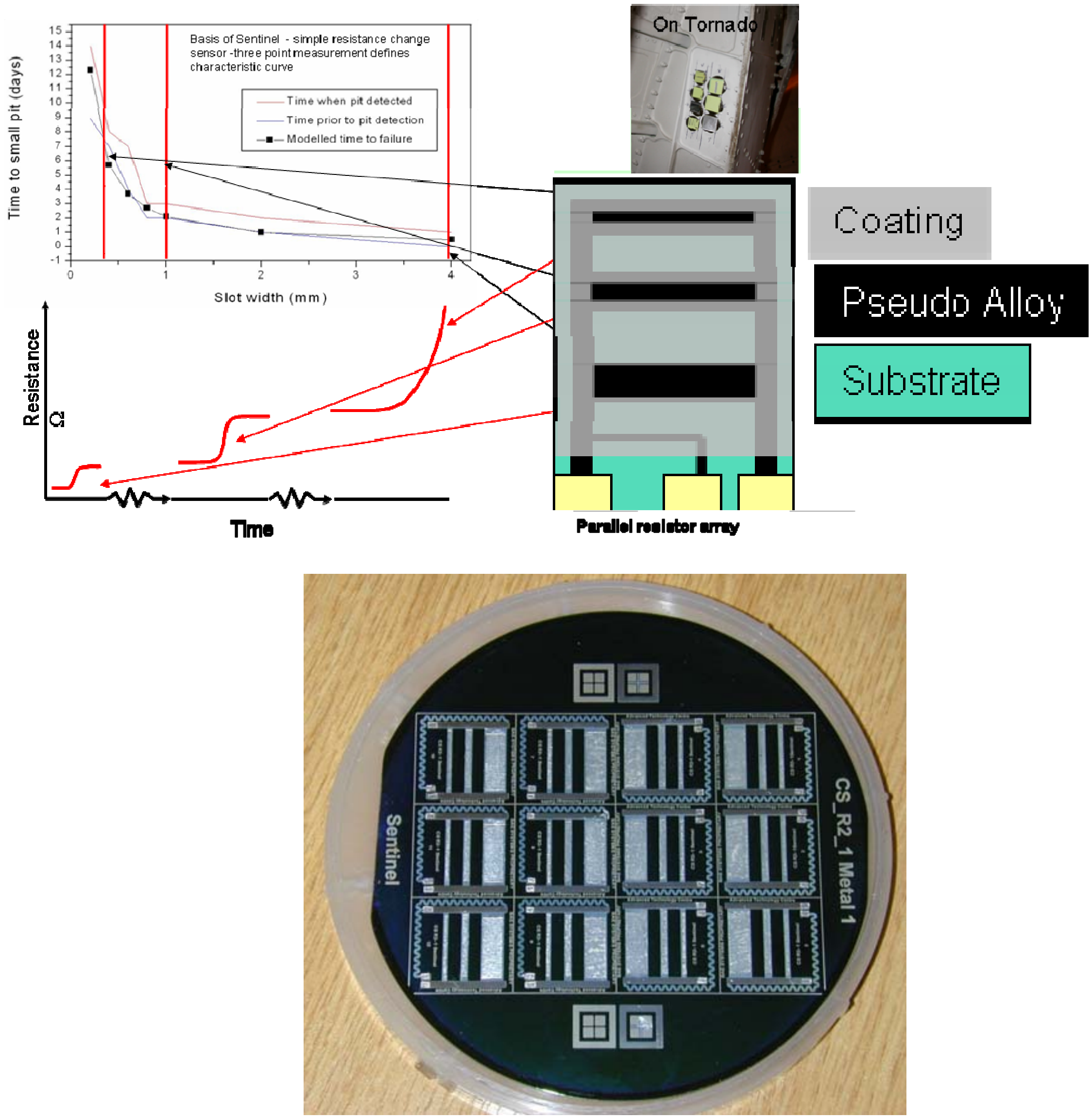

Figure 4: Sentinel coating degradation sensor by BAE Systems. Indicates breakdown of protection scheme, onset of corrosion, and progress of corrosion. Fitted to Tornado, selected by JSF, fitted onto MOD UK land based assets.

Monitoring of basic environmental parameters can be performed with commercial off-the-shelf (COTS) systems such as the datalogger by Zeta-tec illustrated in Figure 5. COTS dataloggers are available for temperature, voltage, resistance, temperature and humidity, event times, etc.

Figure 5: Illustration of a multi-channel/higher performance COTS datalogger systems. COTS dataloggers are available for temperature, voltage, resistance, temperature and humidity, event times, etc.

Future development in corrosion sensor systems could streamline and improve the accuracy of the "usage" and "inspection" functions mentioned above and make it possible to apply them to a larger range of components. The integration of different types of sensor and advanced corrosion modelling could result in further increases in accuracy and scope of application. It could also provide prognostics (estimates of remaining useful life) for corrosion and corrosion/fatigue interaction that would allow corrective action to be planned in advance for efficiency or deferred indefinitely. Groups of sensors can be manufactured on a single chip (Figure 6) and multiplexed for area coverage.

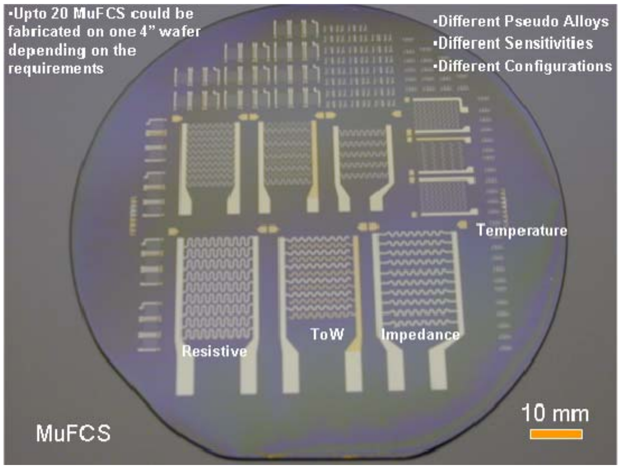

Figure 6: Multifunctional sensor (MuFCS) by BAE Systems - different environmental sensors on a single chip.

No sensor system has yet been able to demonstrate adequate reliability for longer than ten years. There are credible strategies to address this, but it is likely that considerable development will be needed before on-board corrosion sensors can completely replace ground-based inspections for corrosion.

Sensors may not be cost-effective where corrosion can be measured directly and unambiguously, or where very simple indictors only are needed. Also, simple indicators may suffice if combined with a predictive capability and improved knowledge of degradation mechanisms.

5.0 REFERENCES

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