



Australian Government
Department of Defence
Defence Science and
Technology Organisation

Corrosion of Hawk Lead-in-Fighter Hydraulic Pipe Work

A.R. Trueman, G. McAdam and D.R. Gerrard

Maritime Platforms Division
Defence Science and Technology Organisation

DSTO-TR-1833

ABSTRACT

In 2003, corrosion damage to hydraulic and nitrogen pipe work resulted in thirteen RAAF Hawk aircraft being declared unserviceable. The reason for the corrosion was not readily apparent and DSTO was approached to identify the cause and recommend suitable prevention measures. Initial appearances indicated that the corrosion was most likely due to either incorrect use of corrosion protective coatings or their application and/or galvanic corrosion due to exposure in a marine environment. Upon receipt of this task a test programme that involved electrochemical potentiodynamic and galvanic studies, exposure trials of a model of the pipe work and quality control studies of the protective coatings used was initiated to identify the cause of the corrosion. It was concluded from this testing that the premature failure of the Hawk hydraulic fittings was due to galvanic interactions between the cadmium, mild steel and unprotected stainless steel component parts, combined with the use of the aircraft in a coastal location and the cadmium coating thicknesses being below the specified levels. To minimise the risk of further corrosion a suitable coating should be applied to the pipe work adjacent to and over the fitting, the pipe work should be passivated and the specified cadmium coating thickness applied to the fittings.

RELEASE LIMITATION

Approved for public release

Published by

*Maritime Platforms Division
DSTO Defence Science and Technology Organisation
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia*

*Telephone: (03) 9626 7000
Fax: (03) 9626 7999*

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AR-013-593
February 2006*

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Corrosion of Hawk Lead-in-Fighter Hydraulic Pipe Work

Executive Summary

On the 31st July 2003 corrosion damage was discovered on the hydraulic and nitrogen pipe fittings within the main landing gear wheel well of an RAAF Hawk aircraft. Subsequent inspection of the fleet determined that a total of thirteen aircraft were affected and declared unserviceable. An initial investigation by DSTO identified two factors as being possible causes of this corrosion problem:

1. The cadmium-plating used to protect the fitting was damaged and below the specification;
2. The different materials used for the pipe work and the fittings may have been interacting to accelerate the corrosion process

The purpose of the work reported here was to test the conclusions from the initial investigation by performing laboratory-based tests.

On the aircraft components tested, the cadmium-plating was found to be below specification. It was also clearly demonstrated that the interactions between the materials could lead to an acceleration of the corrosion. The corrosion could be reduced by ensuring that the cadmium-plating thickness is within the specified range and ensuring that the lacquer coating applied to the fittings extends onto the pipe work for a few centimetres. The pipe work could also be passivated to reduce the interaction between the materials used. These actions could reduce corrosion and assist with aircraft availability.

Authors

Dr Antony Trueman Maritime Platforms Division

Antony Trueman graduated with a Bachelor of Applied Science (Honours, 1st Class) from the Queensland University of Technology in 1994. He gained a PhD in 1998 also from the Queensland University of Technology for work on the corrosion behaviour of metal matrix composites. Antony joined the Defence Science Technology Organisation in 2003 as a corrosion electrochemist employed to develop corrosion sensors and corrosion models for military platforms. At present he is a Senior Research Scientist in the Maritime Platforms Division and is leading the DSTO effort in corrosion prediction modelling, new corrosion/environmental sensor development and also undertakes fundamental research into the corrosion of metals and alloys used on military ships and aircraft.

Dr Grant McAdam Maritime Platforms Division

Grant completed his PhD at the University in NSW in 1989 in high temperature corrosion. He joined DSTO in 1989 to examine alternative corrosion protective coatings for gas turbine blades. A change in research directions has seen him work in the following areas since 2000: the use of rare earth chemicals for inhibiting corrosion, sensors for the early detection of corrosion, alternatives for chromate containing protective schemes for use on aircraft, corrosion prediction modelling and characterisation of the aircraft operating environment.

Mr Darren Gerrard Maritime Platforms Division

Darren Gerrard is currently a Senior Defence Scientist in the Aircraft Corrosion Control area of DSTO's Maritime Platforms Division at Fishermans Bend, Melbourne, Victoria. His task covers assessment of corrosion prone areas on F-111, C-130 Hercules, P3 Orion, S-70 Seahawk aircraft; investigation of hydrogen embrittlement of high strength steel structures from metal coating processes, aerospace cleaning materials, environmental embrittlement and other processes. It also includes investigation and assessment of alternative coatings including hard chromium and cadmium plating replacements.

Darren holds a Bachelor of Applied Science in Applied Chemistry from the Royal Melbourne Institute of Technology (RMIT) (1981), a Graduate Diploma in Metal Finishing and Surface Protection from RMIT (1987) and awarded the Taubmans Prize for Top Student in Metal Finishing II, and a Master of Engineering Science in Materials Engineering from Monash University (2002).

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1. Introduction

On the 31st July 2003 corrosion damage was discovered on the swaged hydraulic and nitrogen pipe fittings within the main landing gear wheel well of an RAAF Hawk aircraft. Subsequent inspection of the remainder of the fleet identified this problem as being widespread with most aircraft being affected. A total of thirteen aircraft from 76 SQN and two aircraft from 79 SQN were declared unserviceable. An initial investigation by DSTO [1] identified two factors as being possible contributors to the corrosion problem. The first involved damage to the corrosion protection scheme, and cadmium-plating measured to be below specification in some regions of the pipe fittings. Secondly, that there may have been galvanic interaction between the pipe and pipe fitting leading to an acceleration of the corrosion rate. To gain a better understanding of the failure of these fittings, a short scientific investigation was undertaken and is reported in this document.

2. Experimental Methods

2.1 Test alloys and metals

The pipe work which carries hydraulic fluid and nitrogen consisted of piping manufactured from BS T72 stainless steel and swaged unions and nipples manufactured from BS S154 alloy steel. It was not known if the stainless steel had been passivated. The swaged unions and nipples were protected with a cadmium coating that was chromate conversion coated (CCC) and a polyurethane lacquer. Figure 1 shows a pipe fitting with white, grey and brown/red corrosion product, indicative of both cadmium and steel corrosion.

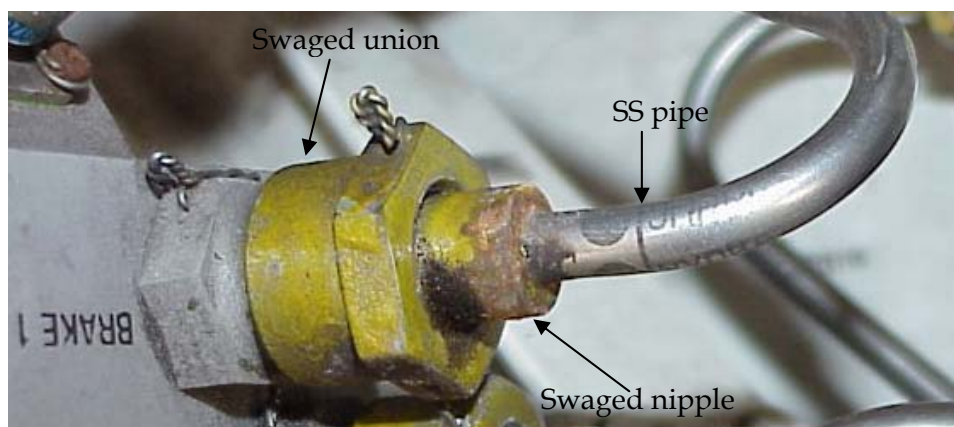


Figure 1: Corroded pipe fitting

The testing was completed using materials as close as possible in composition to those materials used in the Hawk aircraft. The stainless steel used was SS321(Ti) which was the closest available match to BS T72 and the alloy steel selected was AISI 4340, a similar steel to

the BS S154. The compositions of the materials used and those from the aircraft components are listed in Table 1.

Table 1: Composition of alloys used during the test programme compared with those used in the Hawk aircraft

Alloy	Weight %									
	Fe	Cr	Mn	Mo	Ni	P	S	Si	C	Others
BS T72*	Bal.	17-19	0.5-2.0	-	9-12	Max 0.035	Max 0.025	0.2-1.0	Max 0.08	Cu Max 0.5 Nb Min [‡] - Max 1.0
SS321 (Ti) [†]	Bal.	17-19	Max 2.0	-	9-12	Max 0.045	Max 0.04	Max 1.0	Max 0.08	Ti Max 0.7
BS S154*	Bal.	0.5-0.8	0.45-0.7	0.45-0.65	2.3-2.8	Max 0.025	Max 0.015	0.15-0.35	0.27-0.35	Al 0.015-0.05
4340 [†]	Bal.	0.7-0.9	0.7	0.2-0.3	1.83	Max 0.035	Max 0.04	0.23	0.37-0.43	-

N.B. * in use on Hawk aircraft

[†] used during test programme

[‡] 10 x carbon content

Cadmium coatings were applied in-house using pure cadmium anodes. The procedure involved an initial scrub in a pumice slurry, an alkaline degrease and an etch in 50% hydrochloric acid for thirty seconds prior to plating. The specimens were then rinsed and plated in a commercial plating solution (Brycad 53, composition 23 g/l cadmium, 120 g/l sodium cyanide, 20 g/l sodium hydroxide and 1 % by volume Brycad brightener). The plating was conducted at 20°C with a current density of 3 A/dm² for 30 minutes. This treatment typically gave a cadmium thickness of 20-25 µm. Chromate conversion coating treatments were undertaken on aluminium samples using a commercial solution, Alodine 1200, and a commercial deoxidiser, Deox7. The procedure involved deoxidation for five minutes at room temperature (22°C) followed by rinsing in running water for 2 minutes and then CCC for two minutes at room temperature. The cadmium electrode was conversion coated using the DEF(STAN) 03-33/1 procedure [2] and passivation of the stainless steel and Hawk hydraulic pipe was achieved by immersion in 25% nitric acid, 2.5% sodium dichromate solution for 20 minutes at 55°C.

2.2 Electrochemical methods

The experimental work undertaken consisted of potentiodynamic polarisation and potential/current galvanic couple experiments.

2.2.1 Potentiodynamic polarisation

Potentiodynamic polarisation experiments were conducted using a Princeton Applied Research Potentiostat model 273 or 273A. A three-electrode electrochemical cell incorporating two carbon rod counter electrodes and a saturated calomel reference electrode, with a Luggin capillary, was employed. All experiments were conducted in filtered seawater obtained from Queenscliff, Victoria. The 800-900 ml volume of seawater was bubbled with air prior to and during the experiment at a rate of approximately 200 ml/min. This rate was sufficient to saturate the solution with air, as indicated by previous experiments. The working electrodes

consisted of an approximately 1 cm^2 area of the metal or alloy of interest manufactured from the end section of bar stock, mounted in an epoxy resin (Buehler Epo-Thin) and ground to a 2400 grit finish on silicon carbide paper.

Potentiodynamic polarisation was completed in two steps, the cathodic scan followed by the anodic scan after the electrode was re-ground. Both scans were performed at a scan rate of 10 mV/minute after one-hour equilibration in the test solution. The cathodic scan consisted of polarisation from the rest potential to a potential 400 mV more negative than the rest potential. The anodic scan consisted of polarisation to positive potentials until a current density of 0.01 A/cm^2 was attained, after which the potential was scanned back to the rest potential. Potentiodynamic polarisation experiments were conducted upon bare and CCC cadmium, untreated and passivated stainless steel SS321(Ti), alloy steel 4340 and sections of Hawk hydraulic pipe received from the RAAF. The pipe sections were tested in the as-received condition and after passivation.

2.2.2 Potential/current galvanic experiments

Potential/current galvanic experiments were conducted using a Solartron 1287 Electrochemical Interface. A three electrode cell was used, with the more noble metal connected as the working electrode and the more active metal connected to ground. The mixed potential of the couple was monitored using a saturated calomel electrode along with the current flow between the active and noble metals monitored using a zero resistance ammeter. The solution used was air bubbled, filtered seawater obtained from Queenscliff, Victoria. The metal electrodes were manufactured from rod turned in a lathe and ground to a 1200 grit finish on silicon carbide paper, this finish being the finest attainable on the cylindrical electrodes. One end of the rod was mounted in epoxy resin to mask it from the test solution and the remainder was divided in equal sections of 3 cm^2 along its length as shown in Figure 2. The metal rod electrodes were suspended in the electrolyte so as to expose different areas to solution. In this way it was possible to easily alter the ratio of noble to active metal area and to measure the resulting mixed potential and current flow between the active and noble electrodes. Typically the current and potential response was measured for 150 seconds.

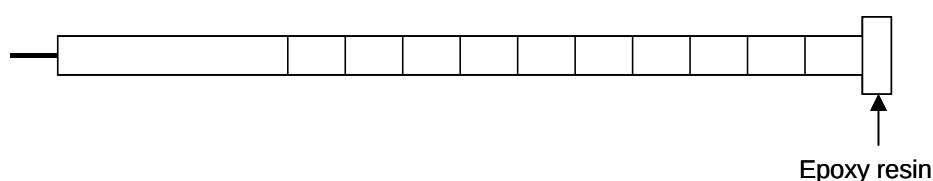


Figure 2: Schematic of a galvanic rod electrode

2.3 Tests in humid air

Tests in humid air were conducted on specimens designed to be analogues of the Hawk LIF hydraulic pipes. The specimens were made of SS321(Ti) rods ground to a 2400 grit finish on silicon carbide paper with no passivation treatment, a similar finish to the as drawn Hawk

Lead in Fighter (LIF) hydraulic pipes. The specimens were electroplated with cadmium to a thickness of approximately 25 μm for half of their length. The cadmium surfaces of some specimens were chromate conversion coated. All specimens were dipped in seawater and dried prior to exposure in an 85% relative humidity atmosphere. Photographs of the specimens were taken after 10 and 46 days of exposure.

2.4 Cadmium thickness measurements

X-ray fluorescence was used to measure the cadmium coating thickness on swaged unions and nipples fitted to pipe work removed from service (P/N: KB290K0026-178, corroded pipe from aircraft A27-17) and also on a new pipe work sample supplied by the TFSP0 (P/N: KB290L004-146). Cadmium thickness measurements were taken on the hydraulic fittings using a UPA Veeco XRF-300AT thickness analyser, using a beam size of 0.3 mm and measurement time of 30 seconds. The instrument was calibrated using cadmium on steel standards with certified thicknesses of 4.62, 12.4, 22.6 and 38.4 μm .

The measurements were made on areas where the cadmium plating appeared intact, with a CCC present and no white corrosion products.

3. Results

3.1 Electrochemical Results

3.1.1 Potentiodynamic polarisation

The combined anodic and cathodic potentiodynamic polarisation scans for cadmium, CCC cadmium, alloy steel 4340 and stainless steel SS321(Ti) are displayed in Figures 3-6 respectively. The values of the corrosion, pitting and protection potentials together with the corrosion, passive and cathodic currents are listed in Table 2. These values were determined from the potentiodynamic polarisation scans.

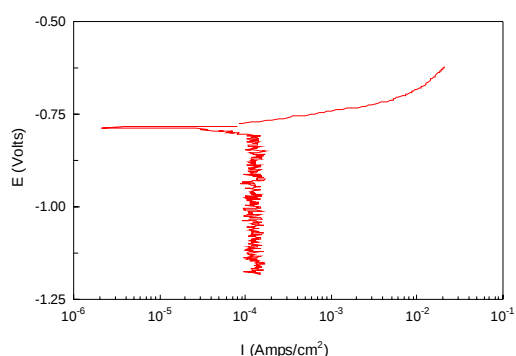


Figure 3: Combined polarisation diagram for cadmium

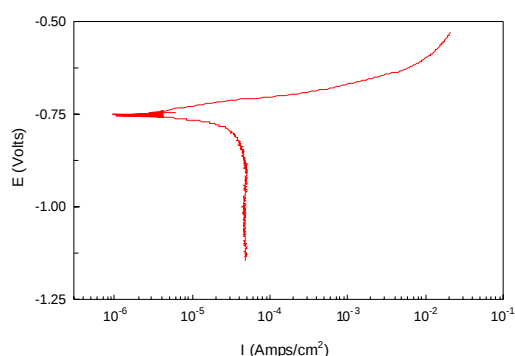


Figure 4: Combined polarisation diagram for CCC cadmium

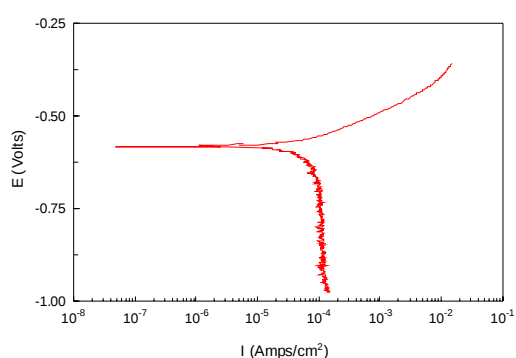


Figure 5: Combined polarisation diagram for alloy steel 4340

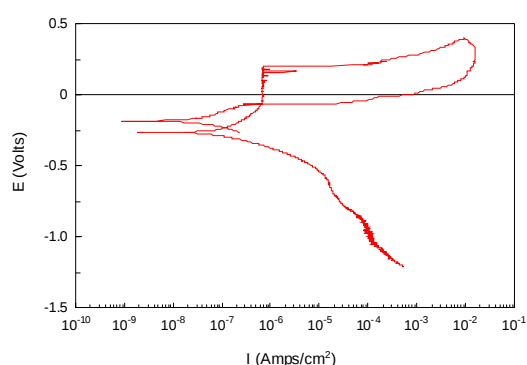


Figure 6: Combined polarisation diagram for stainless steel SS321(Ti)

Table 2: Corrosion, pitting and protection potentials, and corrosion, passive and cathodic currents as determined from Figures 3-6

	Corrosion potential (V)	Pitting potential (V)	Protection potential (V)	Corrosion current (A/cm²)	Passive current (A/cm²)	Cathodic current (A/cm²)
Cadmium	-0.773	N/a	N/a	1.03×10^{-4}	N/a	1.45×10^{-4}
CCC Cadmium	-0.742	-0.715	N/a	5.67×10^{-6}	N/a	4.96×10^{-5}
Alloy steel	-0.578	N/a	N/a	5.15×10^{-5}	N/a	9.97×10^{-5}
Stainless steel	-0.262	0.201	-0.06	2.83×10^{-7}	6.75×10^{-7}	9.73×10^{-5}

The potentiodynamic polarisation results indicate that stainless steel had the highest corrosion potential (most positive) compared to cadmium and the alloy steel and was therefore the most noble. The cadmium, with and without the CCC, had the lowest corrosion potential and was therefore the most active. When coupled, the metal with the more noble potential will become a net cathode and the metal with the more active potential will become a net anode. This will result in a reduction in the corrosion rate of the noble metal and an increase in the corrosion rate of the active metal. The cathodic current density for cadmium was highest and the CCC

cadmium had the lowest cathodic current density. The cathodic current density is important when looking at galvanic corrosion interactions, as it is a measure of the rate at which cathodic reactions, in this case the reduction of oxygen, can take place on the metal surface. When two metals are coupled, the limiting cathodic current density of the more noble metal will support the corrosion rate of the more active metal.

Since stainless steel is the most noble of the metals in the group, its cathodic behaviour is important, as it will support the anodic or metal dissolution reactions on the more active metals. To minimise the cathodic reaction rates on stainless steel, surface treatments have been developed. The passivation treatment thickens the protective oxides on stainless steel resulting in a less efficient surface for electron transfer to cathodic reactants, which leads to a reduction in the rate of these reactions. A further set of cathodic polarisation tests were conducted to determine the effectiveness of a typical passivation treatment on the stainless steel. The cathodic polarisation curves for passivated and non-passivated stainless steel are shown in Figure 7.

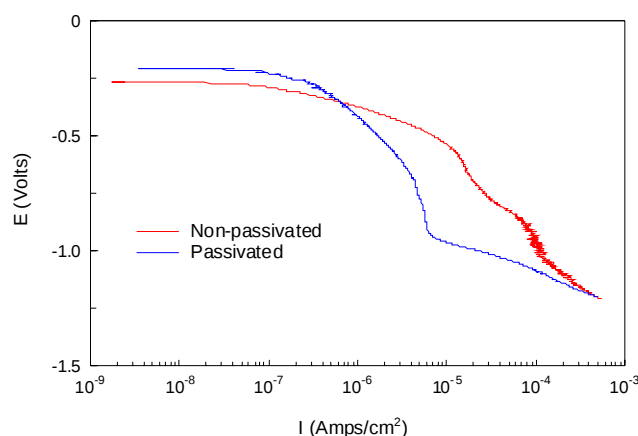


Figure 7: Cathodic polarisation curves for passivated and non-passivated stainless steel SS321(Ti)

Figure 7 shows a significant change in the cathodic polarisation behaviour for the passivated stainless steel compared to the unpassivated stainless steel. The cathodic limiting current for the oxygen reaction on the stainless steel was reduced from 9.73×10^{-5} (non-passivated) to 5.84×10^{-6} A/cm² (passivated). This reduction indicates that the passivated stainless steel is a less efficient cathode and would not accelerate the corrosion rate of coupled active metals to the same degree as unpassivated stainless steel.

Numerous attempts were made to ascertain whether the stainless steel used in the Hawk had undergone a passivation treatment, but no information was received from the RAAF or BAE SYSTEMS. To test for this, and to determine the effect of the passivation treatment, cathodic polarisation tests were conducted upon the as-received stainless steel pipe and on samples of pipe which were chemically passivated. The results are shown in Figure 8.

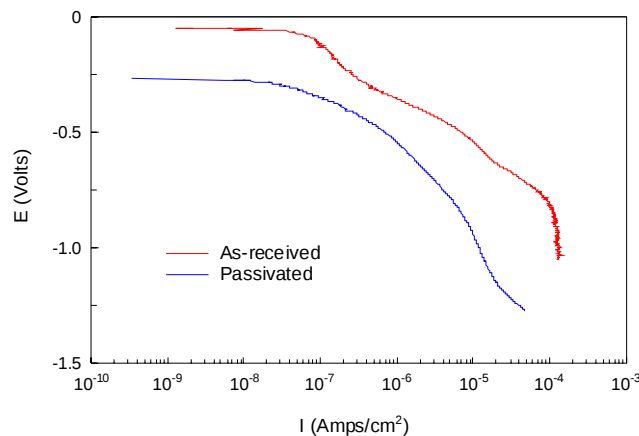


Figure 8: Cathodic polarisation curves for passivated and non-passivated stainless steel BS T72

The results shown in Figure 8 indicate a change in the cathodic polarisation behaviour of the pipe before and after the passivation treatment. The limiting cathodic current density was reduced from $1.16 \times 10^{-4} \text{ A/cm}^2$ for the as received pipe to $1.28 \times 10^{-5} \text{ A/cm}^2$ after passivation, a 10-fold reduction after the passivation treatment. This indicates that the stainless steel pipes were either not passivated, or any passivation treatment was no longer effective, when the pipe was tested.

3.1.2 Galvanic potential and current tests

The potentiodynamic polarisation data, shown in Table 2, indicate large enough differences in the corrosion potentials of the metals for galvanic corrosion to take place. The rate at which the coupling could accelerate the corrosion of the active metals within these couples was determined. This involved measuring the potentials of metal couples and the current flowing for anode to cathode area ratios of between 1:10 and 10:1. The relative cathode and anode areas in a galvanic couple can significantly affect the corrosion behaviour of the anode. The results of the galvanic potential and current experiments for couples with as received and passivated stainless steel and cadmium (bare and CCC) are shown in Figures 9-12.

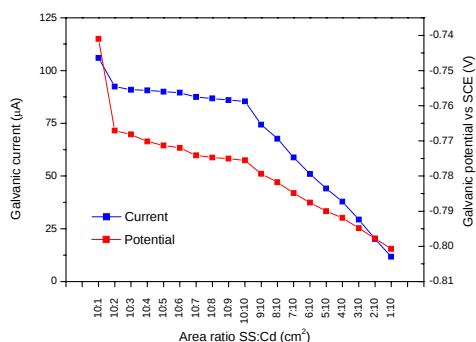


Figure 9: Potential and current flow for the stainless steel/cadmium couple

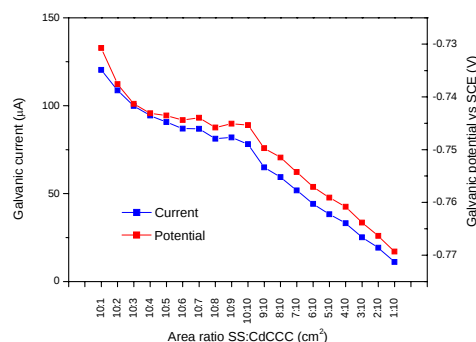


Figure 10: Potential and current flow for the stainless steel CCC/cadmium couple

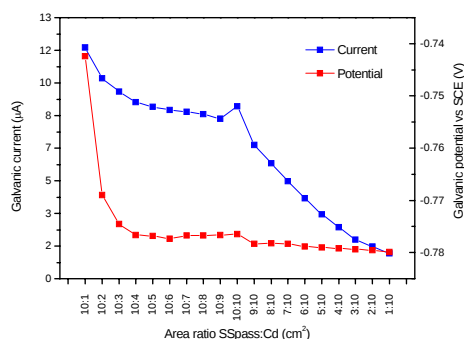


Figure 11: Potential and current flow for the stainless steel (passivated)/cadmium couple

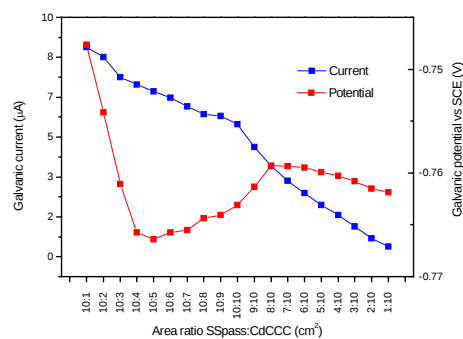


Figure 12: Potential and current flow for the stainless steel (passivated)/CCC cadmium couple

The data shown in Figures 9-12 was used to calculate the anodic current density of the bare cadmium and CCC cadmium when coupled to stainless steel (passivated and non-passivated) as well as the net loss in cadmium thickness. This was achieved by dividing the galvanic current for the different area ratios, shown in Figures 9-12, by the area of exposed cadmium. This current was then added to the corrosion current listed in Table 2, measured from the potentiodynamic diagrams in Figures 3 and 4. The Faraday equation was employed to convert the current density into mass loss. The loss in thickness was calculated using the density of cadmium. The results for the four couples of interest, cadmium (bare and CCC) versus stainless steel (passivated and non-passivated) are shown in Figures 13-16.

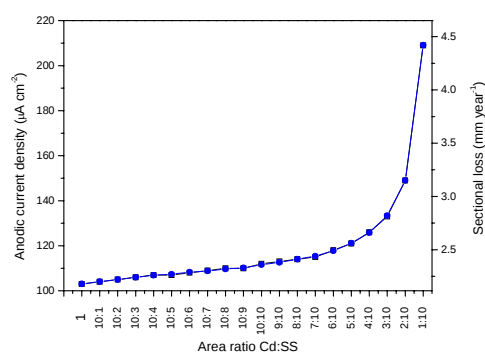


Figure 13: Anodic current density and rate of thickness loss for cadmium coupled to stainless steel

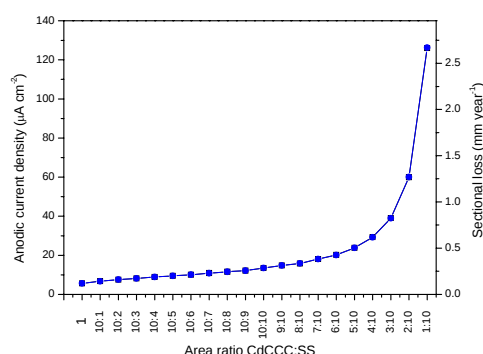


Figure 14: Anodic current density and rate of thickness loss for CCC cadmium coupled to stainless steel

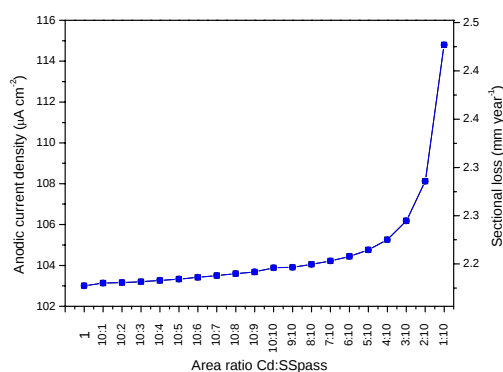


Figure 15: Anodic current density and rate of thickness loss for cadmium coupled to stainless steel (passivated)

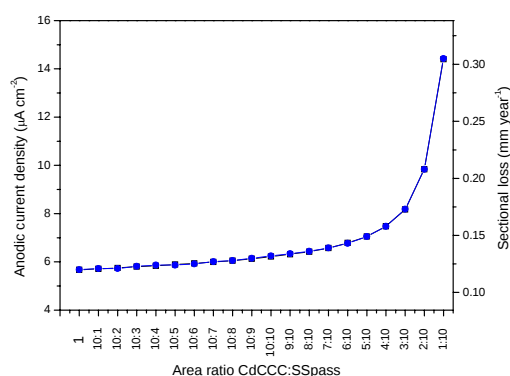


Figure 16: Anodic current density and rate of thickness loss for CCC cadmium coupled to stainless steel (passivated)

The galvanic couple results indicate that, for the bare cadmium non passivated stainless steel combination with a 1:1 (10:10) area ratio, the corrosion rate of the cadmium was $110 \mu\text{A}/\text{cm}^2$ compared to $103 \mu\text{A}/\text{cm}^2$ for uncoupled cadmium; with a ratio of 1:10, the corrosion rate of the cadmium was $210 \mu\text{A}/\text{cm}^2$, twice the uncoupled rate. In the case of CCC cadmium the uncoupled corrosion rate was much lower at $5.7 \mu\text{A}/\text{cm}^2$, and for the 1:1 and 1:10 area ratios with non passivated stainless steel the corrosion rate increased to 13.5 and $126 \mu\text{A}/\text{cm}^2$ respectively. This equated to a 2.5 and 20 fold increase in the uncoupled corrosion rate. For the passivated stainless steel coupled to bare cadmium the corrosion rates were 103, 104 and $115 \mu\text{A}/\text{cm}^2$ for the uncoupled cadmium, 1:1 and 1:10 area ratios respectively, only small increases. The CCC cadmium/passivated stainless steel combination the corresponding values were 5.7, 6.2 and $14.4 \mu\text{A}/\text{cm}^2$ for the uncoupled CCC cadmium, 1:1 and 1:10 area ratios respectively a slight increase for the 1:1 area ratio and a 2.5 fold increase for the 1:10 area ratio. In the non passivated state the stainless steel increased the corrosion rate of bare cadmium slightly and the CCC cadmium significantly. However, the passivation treatment

substantially decreased this galvanic effect as indicated by a corrosion rate of $14.4 \mu\text{A}/\text{cm}^2$ for a 1:10 area ratio compared to $126 \mu\text{A}/\text{cm}^2$ without the passivation treatment.

Also of interest is the galvanic couple between non passivated stainless steel and 4340 alloy steel, as the alloy steel substrate could be coupled to the stainless steel if the cadmium is removed by corrosion. The potential and current flowing for the various area ratios of the alloy steel/stainless steel couple are shown in Figure 17. The anodic current density of the alloy steel and its thickness loss calculated for the range of area ratios is shown in Figure 18.

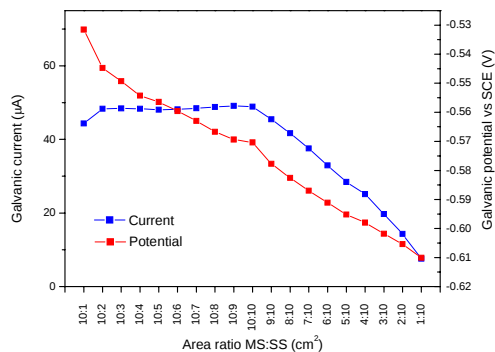


Figure 17: Potential and current flow for stainless steel alloy steel couple

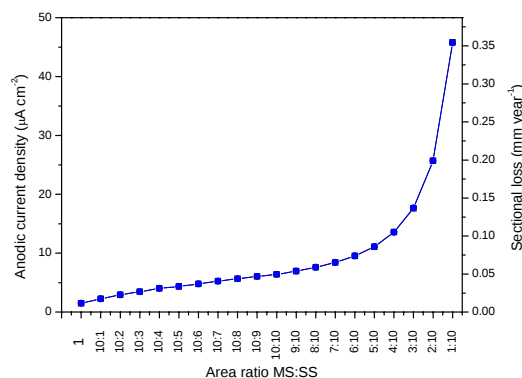


Figure 18: Anodic current density and rate of thickness loss for alloy steel stainless steel couple

The results of the galvanic coupling of stainless steel to alloy steel indicate that the alloy steels corrosion rate will be increased from the uncoupled rate of $1.5 \mu\text{A}/\text{cm}^2$ to rates of 6.4 and $46 \mu\text{A}/\text{cm}^2$ for the 1:1 and 1:10 area ratios of mild steel to stainless steel respectively a 4 and 30 fold increase.

The results of coupling the cadmium to alloy steel indicate that the corrosion rate of the cadmium was increased from 110 to $181 \mu\text{A}/\text{cm}^2$ and $1070 \mu\text{A}/\text{cm}^2$ for area ratios of 1:1 and 1:10 respectively (Figures 19-22). The acceleration of the corrosion rate of CCC cadmium is from a base rate of 5.7 to $63 \mu\text{A}/\text{cm}^2$ and $790 \mu\text{A}/\text{cm}^2$ for area ratios of 1:1 and 1:10 respectively, a 10 and 140 fold increase respectively. In this testing a large increase in the galvanic potential was witnessed as the cadmium area was increased beyond the 1:1 area ratio that may have been due to oxide formation on the alloy steels surface.

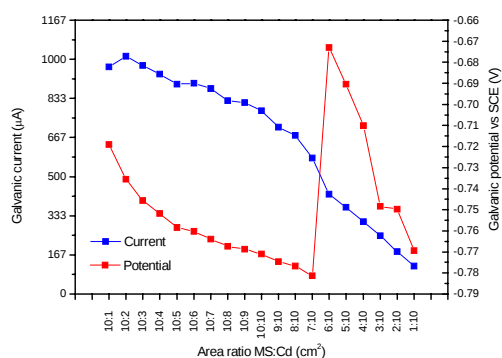


Figure 19: Potential and current flow for the alloy steel/cadmium couple

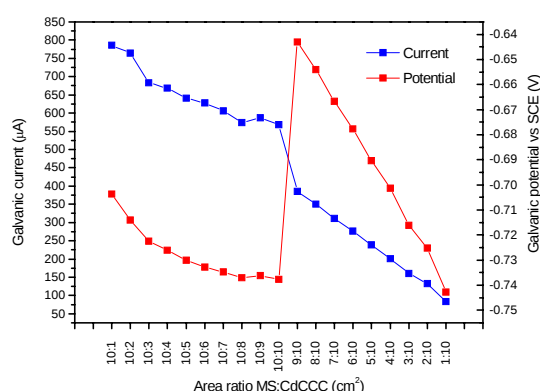


Figure 20: Potential and current flow for mild steel/CCC cadmium couple

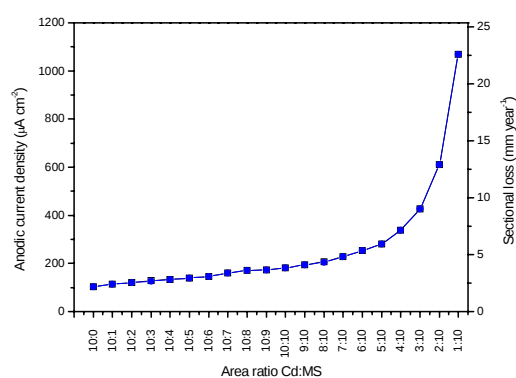


Figure 21: Anodic current density and rate of thickness loss for alloy steel/cadmium couple

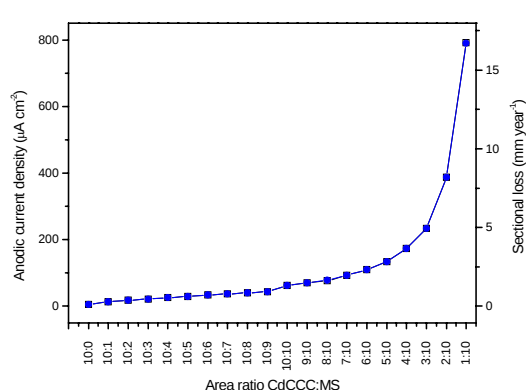


Figure 22: Anodic current density and rate of sectional loss for alloy steel/CCC cadmium couple

3.1.3 Tests in humid air

These tests were conducted in an attempt to replicate the type of conditions the hydraulic pipes and fittings would experience in service. That is, contamination with seawater to leave salt residue and exposure to a moist environment. The specimens were left in the humid environment and the corrosion damage assessed on two occasions. After 10 days, white corrosion products typical of cadmium hydroxide and brown-black corrosion product typical of cadmium oxide were observed at the cadmium/stainless steel interface. There was little cadmium corrosion product observed away from this interface indicating that galvanic interaction at the interface had produced the corrosion of the cadmium. Images of this corrosion are shown in Figures 23 and 24 for the bare cadmium and CCC cadmium specimens respectively. The specimens after 46 days of exposure showed extensive corrosion product formation, with black corrosion product more prevalent (Figures 25 and 26). Since no corrosion of cadmium away from the interface was observed, it is concluded that the contact between the cadmium and the stainless steel was responsible for the accelerated corrosion of the cadmium.

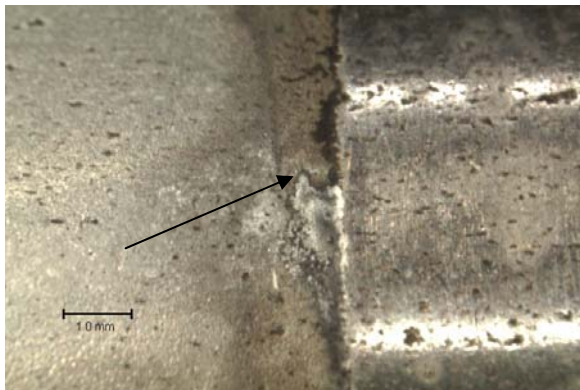


Figure 23: Corrosion of cadmium coated stainless steel after 10 days in 85% RH air

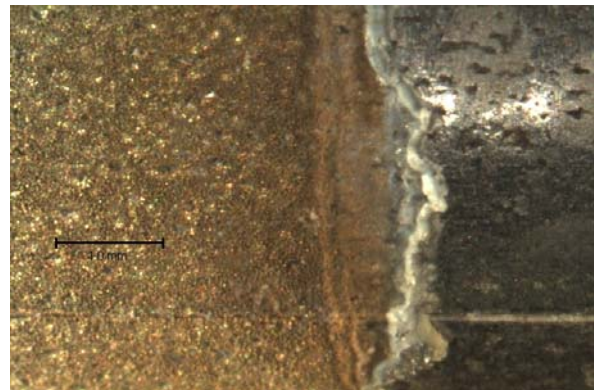


Figure 24: Corrosion of CCC cadmium coated stainless steel after 10 days in 85% RH air

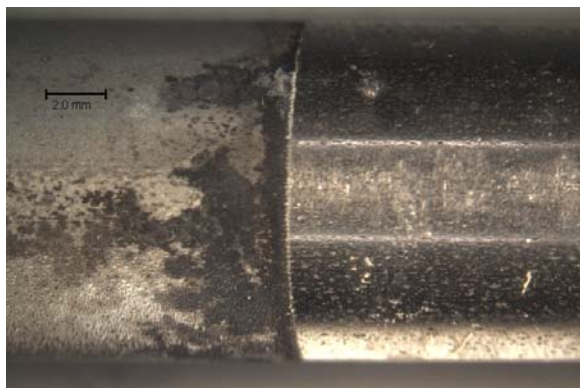


Figure 25: Corrosion of cadmium coated stainless steel after 46 days in 85% RH air

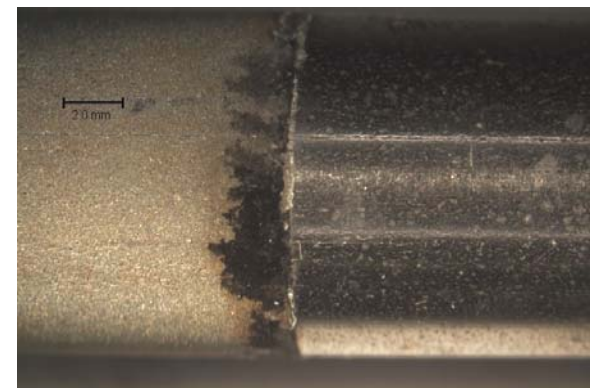


Figure 26: Corrosion of CCC cadmium coated stainless steel after 46 days in 85% RH air

The distance that corrosion extended from the cadmium/stainless steel interface was approximately 3-4 mm. This is in agreement with the theoretical calculation of 3.5 mm over which the galvanic interaction between cadmium and stainless steel may extend when covered by a thin moisture film (Appendix A).

3.2 Cadmium thickness measurements

For pipe-work and fittings removed from service, the measurements were made at both ends of the pipe-work as there were significant differences in the extent of corrosion damage. The minimum thickness for cadmium coatings as detailed in DEF(STAN) 03-19/2, Amendment 1 (21/11/96) [3] is 10 μm for pipes, an average minimum thickness of 14 μm for the swaged nipples and a minimum thickness of 6.5 μm for the swaged unions. The cadmium thickness was measured at several locations around the swaged union as detailed in Figures 27 and 28.

The average measured cadmium thicknesses for the corroded and new fittings are displayed in Tables 3 and 4 for both the unions and the nipples. The cadmium coating was CCC.

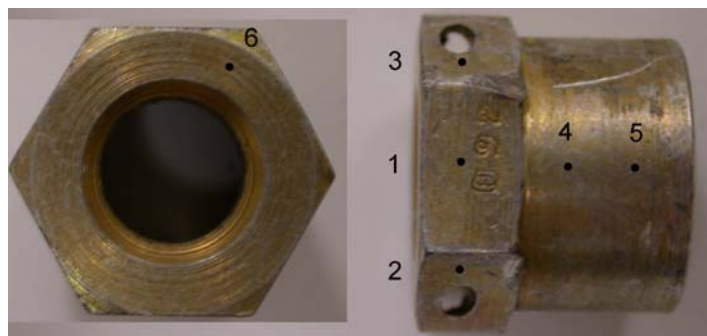


Figure 27: Cadmium thickness measurement locations on swaged union

Table 3: Cadmium thickness on swaged unions at locations shown in Figure 27

Location	Average Thickness from 3 measurements, μm		
	As new component	Least corroded end from Hawk A27-17	Most corroded end from Hawk A27-17
1	13.1	5.2	2.9
2	13.5	5.1	2.7
3	9.0	5.1	3.3
4	10.0	4.0	2.7
5	10.0	4.4	3.5
6	Not accessible	4.2	2.4

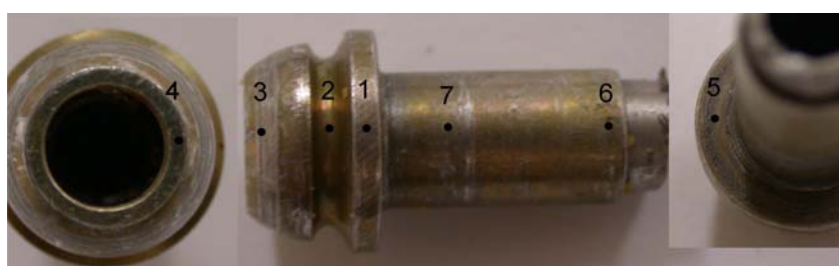


Figure 28: Cadmium thickness measurement locations on swaged nipple

Table 4: Cadmium thickness on the swaged nipples at locations shown in Figure 28

Location	Average Thickness from 3 measurements, μm		
	As new component	Least corroded end from Hawk A27-17	Most corroded end from Hawk A27-17
1	10.0	3.3	3.3
2	7.4	3.2	3.2
3	11.0	3.4	3.1
4	Not accessible	2.9	2.5
5	Not accessible	2.7	2.0
6	13.0	4.9	Corroded
7	8.0	3.9	Corroded

The cadmium plating thicknesses on the unions and nipples were less than the minimum requirements of DEF(STAN) 03-19/2, Amendment 1 (21/11/96). The cadmium plating thickness measurements taken on the swaged unions of as new pipe work, supplied by TFSPO, were greater than the minimum requirements of DEF(STAN) 03-19/2, Amendment 1 (21/11/96). The thickness measurements taken from the swaged nipples on the new pipe work were generally greater than the minimum requirements, with the exceptions of locations 2 and 7.

4. Discussion

The potentiodynamic polarisation results indicate that the cadmium coated 4340 steel coupled to stainless steel will act as the anodic part of a galvanic couple. This coupling will cause accelerated corrosion of the cadmium. The 4340 steel will also couple to the stainless steel again forming the anodic portion of the couple.

The potential/current galvanic experiments indicated that an increase in the cadmium corrosion occurred when it was coupled to stainless steel. This increase was governed by the relative areas of the couples and was greater when CCC cadmium was coupled to stainless steel, up to a 20-fold increase in the case of a 1:10 cadmium/stainless steel area ratio. The galvanic effects were markedly diminished by the passivation of the stainless steel, with the increase in corrosion rate being only 2.5 times that of the uncoupled CCC cadmium rate at the 1:10 area ratio.

The alloy steel nipples and unions will corrode more rapidly if coupled to stainless steel, a 30-fold increase for a 1:10 area ratio of alloy to stainless steels. However, once the alloy steel is exposed, the cadmium will corrode at a faster rate to protect the steel, as designed, and a three metal galvanic couple will be established. The alloy steel is a more efficient cathode than stainless steel and would increase the corrosion of any remaining cadmium above the rate due to the coupling with stainless steel.

The exposure tests showed that galvanic corrosion occurs in high humidity atmosphere with cadmium coupled to stainless steel and salt contaminant present. It was also shown that the

galvanic interaction occurred over a short distance of approximately 3-4 mm from the galvanic interface. It therefore follows that if the stainless steel was painted for at least this distance, the corrosion may not occur. This has subsequently been confirmed by correspondence with BAE SYSTEMS which stated that corrosion of the hydraulic parts was not a problem in the RAF fleet [4]. An image of an in-service part supplied by BAE SYSTEMS clearly indicated a protective coating present over the first few centimetres from the swaged galvanic interface. A protective coating applied in this manner will prevent galvanic interaction between the cadmium and the stainless steel in atmospheric conditions.

The cadmium plating thickness on ex-service hydraulic fittings was less than the specified requirement. The measurements were taken on surfaces that appeared not to have degraded in service (eg. internal surfaces not exposed to the corrosive environment). Therefore the low cadmium thicknesses were as manufactured.

This work has shown that the corrosion of the Hawk hydraulic fittings was due to a combination of several factors:

- The use of dissimilar metals i.e. CCC cadmium in contact with stainless steel caused galvanic corrosion.
- The use of stainless steel without passivation or a protective coating increased the corrosion rate of the cadmium.
- The below specification cadmium coating thickness, lead to premature removal of the cadmium.
- The location of the aircraft, close to the sea in a salt laden atmosphere, ensured the presence of a thin moisture film to support the corrosion.

Several steps may be taken to minimise or prevent future corrosion problems.

1. If a suitable coating is applied to the first few centimetres of stainless steel pipes adjacent to the swaged connections, the risk of galvanic corrosion will be reduced. An alternative is to use a corrosion prevention compound conforming to Boeing Material Specification BMS 3-35, for example: Dinitrol AV15 or Cor-Ban 35.
2. If the stainless steel pipes are given a suitable passivation treatment, then any failure of the coating applied in step 1 should not result in significant corrosion of the cadmium.
3. Ensuring that the unions and nipples have the correct cadmium coating thickness will extend the life of the fittings.

5. Conclusions

The premature failure of the Hawk LIF hydraulic fittings was due to galvanic corrosion interactions between the cadmium, mild steel and unprotected stainless steel components, combined with a cadmium coating thickness below specification and the use of the aircraft in a coastal location. The failures can be prevented in future by the use of a suitable coating applied to the stainless steel pipe adjacent to the swage, the use of passivated stainless steel piping and the correct cadmium coating thicknesses applied to the fittings.

6. References

- 1 S. Grummett, G. McAdam *LIF Hawk Corrosion of Hydraulic Union Fittings Investigation* Aircraft Forensic Engineering MET 054/2003, 21 August 2003
- 2 DEF(STAN) 03-33/1 *Chromate Passivation of Cadmium and Zinc Surfaces*, 26 November 1993
- 3 DEF(STAN) 03-19/2 *Electro-deposition of Cadmium*, 31 March 1994
- 4 M. Uttley *Fault Investigation Report, Royal Australian Air Force, Corroded Hydraulic Pipes in Undercarriage Bay*, BAES-BAW-RP-HWK-1746, 10 October 2003

Appendix A: Calculation of range of galvanic couple

To determine the range over which galvanic interactions can occur the contact potential difference in aerated seawater was measured for the cadmium stainless steel couple. This was found to be approximately 500 mV. The current flowing between these two metals when coupled was also measured and found to be approximately 5 μ A. For this couple the resistance is therefore:

$$\text{Resistance} = 500 \text{ mV} / 5 \mu\text{A} = 100\,000 \Omega$$

Also from previous studies a typical surface coverage of salt could be 20 $\mu\text{g}/\text{cm}^2$ and that this would form a 1 M solution when exposed to 95% relative humidity. The thickness of this solution can then be calculated as follows:

$$\text{Thickness} = 20 \mu\text{g} / (58(\text{molecular mass NaCl}) \times 1000) = 3.5 \times 10^{-4} \text{ cm or } 3.5 \mu\text{m}.$$

Using the conductivity of a 1 M NaCl solution of 0.01 S cm^{-1} the resistance of a 1 cm cross section of the surface moisture film 1 cm long was estimated to be:

$$\text{Moisture resistance} = 1 \text{ cm} \times 1 / (0.01 \text{ S cm}^{-1} \times 3.5 \times 10^{-4} \text{ cm} \times 1 \text{ cm}) = 285714 \Omega$$

The distance over which current can be transferred through this thin moisture film is therefore the resistance divided by the moisture resistance and is equal to 0.35 cm.

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A.R. Trueman, G. McAdam and D.R. Gerrard

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2. TITLE Corrosion of Hawk Lead-in-Fighter Hydraulic Pipe Work			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)						
4. AUTHOR(S) A.R. Trueman, G. McAdam and D.R. Gerrard			5. CORPORATE AUTHOR DSTO Defence Science and Technology Organisation 506 Lorimer St Fishermans Bend Victoria 3207 Australia						
6a. DSTO NUMBER DSTO-TR-1833		6b. AR NUMBER AR-013-593		6c. TYPE OF REPORT Technical Report		7. DOCUMENT DATE February 2006			
8. FILE NUMBER 2004/1018707/1		9. TASK NUMBER AIR 02/125		10. TASK SPONSOR DGTA		11. NO. OF PAGES 17		12. NO. OF REFERENCES 4	
13. URL on the World Wide Web http://www.dsto.defence.gov.au/corporate/reports/DSTO-TR-1833.pdf					14. RELEASE AUTHORITY Chief, Maritime Platforms Division				
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19. ABSTRACT In 2003, corrosion damage to hydraulic and nitrogen pipe work resulted in thirteen RAAF Hawk aircraft being declared unserviceable. The reason for the corrosion was not readily apparent and DSTO was approached to identify the cause and recommend suitable prevention measures. Initial appearances indicated that the corrosion was most likely due to either incorrect use of corrosion protective coatings or their application and/or galvanic corrosion due to exposure in a marine environment. Upon receipt of this task a test programme that involved electrochemical potentiodynamic and galvanic studies, exposure trials of a model of the pipe work and quality control studies of the protective coatings used was initiated to identify the cause of the corrosion. It was concluded from this testing that the premature failure of the Hawk hydraulic fittings was due to galvanic interactions between the cadmium, mild steel and unprotected stainless steel component parts, combined with the use of the aircraft in a coastal location and the cadmium coating thicknesses being below the specified levels. To minimise the risk of further corrosion a suitable coating should be applied to the pipe work adjacent to and over the fitting, the pipe work should be passivated and the specified cadmium coating thickness applied to the fittings.									