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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.315

AIRCRAFT CORROSION

Papers presented at the 52nd Meeting of the AGARD Structures and Materials Panel held in Çeşme, Turkey on 5–10 April 1981.

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- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

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PREFACE

Corrosion has been a problem in aircraft structures since the very beginning of modern aviation. While technology has achieved a great deal over the years, it has not been successful in eliminating this problem. In 1976, the Structures and Materials Panel of AGARD sponsored its Lecture Series No. 84, on "The Theory, Significance And Prevention Of Corrosion In Aircraft." The lecture series was well attended, and produced keen interactions between the lecturers and participants in each country (NE, PO, US) where the lectures were held. The Lecture Series Director, Mr. Nathan Promisel (US), and his team, were diligent in their work, and provided to the SMP a series of recommendations for further work that have been the basis of our subsequent efforts.

The subjects covered by these recommendations were diverse. Research and development, generally directed towards improved corrosion resistant materials and protection systems, were high on the list of priorities. The subject of information exchange was included. It was suggested that existing information, particularly that held by the aircraft operators, was often not exploited fully due to our failure to maintain the feed-back loop to the designers, manufacturers and R & D specialists. Since the same corrosion problems tend to recur time and time again, it was recommended that education and re-training be included in future plans.

While the Lecture Series Team was able to identify problems and ways of dealing with them they recognised that the benefits of doing so were less clear. For example the costs of corrosion are not known precisely, and therefore only crude estimates of potential savings can be made. A 1979 study conducted by Battelle Columbus Laboratories on behalf of the National Bureau of Standards has estimated the total cost of corrosion in the US to be $70 billion/year. An unconfirmed report has estimated the total cost of detecting and repairing corrosion in the US Air Force at $1 billion/year, while a 1979 estimate has put the total direct cost of corrosion to IATA member airlines at $100 million based on 1976 operations. Thus the numbers are large, but detailed analyses on specific aircraft types, in known operational roles, are rare. It is difficult therefore to argue with procurement executives the need to spend additional money on more substantial corrosion protection systems, and equally difficult to justify spending more money on R & D. It is also difficult to persuade designers and manufacturers to be more rigorous in their activities, since they may well price themselves out of the market.

The Specialist Meeting on Aircraft Corrosion, held in Cesme, Turkey, April, 1981, is an attempt to contribute in a small way to this major problem. The meeting has been organised in four half-day sessions, in which we have attempted to bring together the operators of civil and military aircraft, their maintenance personnel, the designers and manufacturers of aircraft, and R & D specialists for a free exchange of information and opinion. This published proceedings should provide a detailed account of the state-of-the-art, and a platform from which further work can be launched.

The success of the meeting and the quality of the final publication are due to the authors, session chairmen, recorders and discussors, all of whom have spent many long hours in their repair shops, laboratories and offices. But a special vote of thanks is due to Mr. Tom Kearns of the United States, the former chairman of the Sub-committee on Corrosion. Mr. Kearns understood the problems better than most and he showed his committee what was needed to be done. Through this message we send to Mr. Kearns our sincere thanks, and a wish that he may find time in his retirement to show us the way in the future.

W. Wallace,
Chairman, Sub-committee
on Aircraft Corrosion.
Structures and Materials Panel.

CONCLUDING SUMMARY.

In planning this meeting the Structures and Materials Panel of AGARD and its colleagues were under no illusion that the problem at hand was simple. We knew we would solve few, if any specific problems, but were satisfied that by focussing attention on the corrosion issue, we could help by maintaining an awareness, that in the long term could only be beneficial.

The discussions during this meeting have been spontaneous and productive, and our experts have been in remarkable agreement in their assessment of the problem, and the approaches that we should follow in the future. The following is a summary of the major points of agreement, reached by these specialists, which might be used in planning future actions. It is hoped that these will be considered not only by the Structures and Materials Panel, but also by other organisations in the NATO countries that are concerned with the design, manufacture and use of aircraft. We hope, also, that the recommendations will be considered by our educational institutions and training centres since, as indicated throughout the proceedings and below, education was considered one of the key issues to be tackled.

1. The meeting agreed unanimously that the cost of corrosion was high, but also agreed that it is difficult to demonstrate this in any quantitative way with accurate figures. Better information is required on the cost of corrosion, together with analyses of the trade-off between initial investment in good design and corrosion protection versus later repair.

2. The fundamental corrosion processes are fairly well understood and can generally be reduced to a low level of occurrence. However the same problems tend to occur time and again, indicating that we do not learn from our mistakes. Continuing education is required at all levels, from initial exposure to corrosion at the university undergraduate level, through to re-training of practicing designers, production engineers and maintenance personnel.

3. A specific recommendation, related to item 2 above, was that engineering students should be required to complete a corrosion science course as a prerequisite to a Bachelor of Science degree in Engineering. This would provide the new engineer with a basic knowledge of corrosion and enable him to select the least corrosive metal/material when designing and constructing a structure or equipment. The expected result of this recommendation would be a high reliability product with a longer service life and a lower overall cost of ownership to the user.

4. A further recommendation emerged, which is effectively an extension of the point made in item 2 above. It relates to the need for a continuing effort to maintain the communications link between the users and the manufacturers. It was recommended that the users of civil aircraft be given an opportunity to engage in these exchanges. It was considered that AGARD could contribute to this through its existing projects on the "Corrosion Handbooks," and by additional activities such as the organisation of workshops and discussion groups.

5. It was suggested that there may be no absolute right or wrong with respect to proper design and protection against corrosion, but that many of the recommended practices in effect in some of the larger countries may have particular merits in some, if not all operational circumstances. For the benefit of the smaller countries, these practices and proceedures should be brought together in a single document, and their merits and limits of applicability evaluated by our experts. This might be achieved through a series of workshops involving a relatively small group of people.

6. The ranking of engineering alloys, and protection systems to resist corrosion remains a problem. And this is complicated by the wide variety of different test methods that are available, and used from country to country. The evaluation of standard test methods, such as those recommended by ASTM or AECMA, on an international basis and the correlation of results with service experience is an area worthy of further collaboration.

W. Wallace
G. T. Browne
on behalf of the
Sub-committee on Corrosion,
Structures and Materials Panel.

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Reference

U.S. NAVAL FLEET AIRCRAFT CORROSION

by

G.T.Browne
Materials Consultant
Commander, Naval Air Force, Atlantic Fleet
Norfolk, VA 23511
USA

1. Some of the most severe corrosion problems experienced by the fleet in recent years have been caused by water intrusion into the aircraft and avionics/electrical equipment as illustrated in photographs of equipment and electrical connectors. (See Figures 1 - 10) Water entering through closed access panels has caused internal aircraft corrosion and has infiltrated avionics equipment through the backs of environmental electrical connectors, seals, screw holes, etc., resulting in excessive aircraft down time and extensive repair of avionics components. Considerable progress has been made in minimizing water entry and its associated corrosion problems by a joint effort involving fleet operating and maintenance personnel, people at the Naval Air Development Center (NAVAIRDEVCEN), the principal Navy aeronautical materials laboratory, people of the Naval Air Systems Command (COMNAVAIRSYSCOM), who write the specifications and procure aircraft, the aircraft manufacturers and their subcontractors. The program initially concentrated on the mechanics of water entry, then investigated specific problems in detail to determine corrective action. Some of the results are discussed below:

a. A method for sealing environmental connectors without degrading wire quick disconnect capability was incorporated by sealing the back connector shell rubber grommet with clear room temperature vulcanizing (RTV) silicone type sealant. (See Figure 11) The screw holes and equipment lids were also sealed in a similar manner. This practice has been employed throughout the U. S. Atlantic/Pacific Fleets on several types and models of aircraft, with great success.

b. Another problem associated with water intrusion is water entrapment in an aircraft causing severe corrosion. Working with aircraft design engineers, drain holes have been located and drilled in non-structural areas at low points to remove trapped water and eliminate the corrosive agents.

c. We still see some corrosion from the use of dissimilar metals contact when insufficient sealant is used on faying surfaces as illustrated by photographs of dissimilar metals. Hidden corrosion is detected by nondestructive inspection methods during rework. (See Figures 12 - 16) These include ultrasonic, X-ray and eddy current inspection and neutron radiography on double skin areas and on areas behind stringers, etc. where corrosion is caused by moisture entrapment. Corrosion due to entrapped moisture ranges from light surface corrosion to severe exfoliation, and when discovered, normally requires material replacement by depot activities and the addition of sealants to the faying surfaces. Surface contact type corrosion problems would be minimized by material selection if suspected corrosion prone areas of an aircraft are constructed of less corrosion prone materials, if dissimilar metal contacts are minimized and properly insulated, if better protection is provided for the materials used during construction as illustrated by photographs. (See Figures 17 - 20)

d. Stress corrosion cracking in high strength components is discovered occasionally. However, incidence has declined because of the protection provided by the extensive use of sealants on naval aircraft and the use in later aircraft models of the overaged (T73) tempers in aluminum alloys and new alloys (7050) more resistant to stress corrosion. Most corrosion seen on U. S. naval aircraft results from an uncontrollable source (or operating environment) as illustrated in photographs. (See Figures 21 - 23) In order to minimize corrosion from the operating environment, on older aircraft where new techniques and material have not been employed, the U. S. Atlantic and Pacific Fleets have established detailed corrosion prevention/control programs that involve all levels of command to insure dedicated application and enforcement as discussed below.

e. Standard fleet corrosion maintenance is accomplished in accordance with procedures provided in technical manuals. For aluminum alloys, corrosion is always removed by the mildest means possible. After all visible corrosion is removed, the area is visually inspected with a 10X glass to insure all corrosion products are out of any pits that may be present. When it is determined that all of the corrosion product has been removed, the area is cleaned to a water break free surface in accordance with technical manuals and allowed to dry. A chemical conversion material, MIL-C-81706, is then applied and allowed to dwell 10 to 15 minutes to etch the surface and increase paint adhesion. The work area is then flushed with fresh water, recleaned and allowed to dry. The area is then checked for the golden brown color which is produced by the chemical conversion material. If the work area requires sealing, a polysulfide sealant is then applied and allowed to dry before primer is applied. If sealant is not required, the area is primed and painted with the standard U. S. Navy aircraft finish system, which consists of an epoxy polyamide primer, MIL-C-23377 and a topcoat of an aliphatic polyurethane, MIL-C-81773.

f. The following procedures and tools are provided to the fleet corrosion mechanic:

(1) Paint removal material: Chemical paint remover (preferred).

(2) Corrosion removal:

(a) Hand scrub with dry non-metallic brush for very light surface corrosion.

(b) Hand scrub with nylon pad impregnated with aluminum oxide (used on very heavy surface corrosion).

(c) Flap wheel turned at 3,000 rpm (50 rps) for heavy corrosion in any form. A flap wheel is a nylon wheel impregnated with aluminum oxide.

(d) Glass bead vacu-blast to remove pitting corrosion (sometimes required after the flap wheel has been used for clean-up). The vacu-blast is a system whereby glass beads are propelled at 90 psi (6020 kPa) onto a surface to be cleaned through the inner tube of the device, as the outer tube of the device vacuums up the glass beads and the corrosion product dislodged by the blasting action. Metallic tools are not authorized for use by fleet mechanics for corrosion control.

2. The fleet corrosion prevention/control program is administratively established in accordance with Chief of Naval Operations Instruction 4790.2B and amplified by Commander Naval Air Force, U. S. Atlantic Fleet/Commander Naval Air Force, U. S. Pacific Fleet detail instructions. Technical information is provided in Corrosion Control Cleaning Manuals, NA 01-1A-509 for Aircraft, NA 16-1-150 for Avionics and NA 17-1-125 for Ground Support Equipment. Training for corrosion control supervisors and mechanics is provided by Naval Air Maintenance Training Detachment (NAMTRADET), Naval Air Rework Facility (NAVAIREWORKFAC) and on-site Naval Aviation Engineering Service Unit (NAESU) corrosion specialists. Detailed requirements for operational squadrons are contained in COMNAV-AIRLANT/COMNAVAIRPAC instructions, as follows:

a. Each activity shall establish a corrosion control/prevention program that will function on a day-to-day basis.

b. Corrosion team members shall receive NAMTRADET and NAVAIREWORKFAC on-the-job training before they are considered qualified.

c. Corrosion control officers shall have NAMTRADET training as a minimum (most have the same training as their team members plus an additional management course).

d. Aircraft are inducted for corrosion maintenance by calendar cycle. Once the aircraft is inducted, all corrosion discrepancies within the maintenance level capability are corrected before the aircraft is returned to a flight status. When required, assistance is requested from higher maintenance levels.

e. Emergency reclamation teams are established in each fleet activity operating or supporting aircraft or equipment. Emergency reclamation team consists of the squadron Corrosion Control Officer and one or two mechanics from each rating group. The Team is trained in accordance with NA 01-1A-509 technical manual emergency procedures for reclaiming airframe, engine, avionic and other aircraft components that have been exposed to ususually severe corrosive conditions, e.g., salt water immersion, fire extinguishing agents. Team reaction is as soon as possible after exposure.

f. Shelf life of corrosion materials, storage and flammable materials is also addressed in the instruction.

3. COMNAVAIRLANT/COMNAVAIRPAC also host an annual corrosion workshop for Atlantic and Pacific functional wings and squadrons. Normally, presentations are provided by NAVAIR-SYSCOM, NAVAIRDEVCEN, NAVAIRENGCEN, NAVSUPSYSCOM, NAESU and Navy Environmental Health Center. Topics covered during workshop: new corrosion prevention material, new paint systems, new procedures, problems encountered and corrective actions taken are discussed quite often, answers are provided to correct reported problems, new equipment, Navy shelf life program, training and health hazards that may be expected with some of the new material being introduced and safety precautions required.

4. COMNAVAIRLANT/COMNAVAIRPAC Material Condition Audit Program is another aspect of the Navy Corrosion Control Program and has proven to be beneficial to COMNAVAIRLANT/COMNAVAIRPAC and to operating activities. In that COMNAVAIRLANT/COMNAVAIRPAC know the condition of fleet aircraft, assistance is provided to squadrons by the audit team when required. Each functional wing has an audit team with an aircraft maintenance officer as audit team leader. Other audit team members are chief petty officers, E-7/E-8/E-9. Normally, the enlisted members have been with the aircraft type a number of years. Many have in excess of 20 years naval aviation experience.

a. Pre-deployment, mid-deployment and post-deployment audits are conducted on deploying tactical air activities whenever a deployment is in excess of five months.

b. Non-deploying activities and intermediate maintenance activities are audited semiannually. Special programs, i.e., water intrusion, avionics cleaning/corrosion prevention, hydraulic contamination, aircraft tire/wheel safety and nondestructive inspection are reviewed with the audited activity concurrently.

c. Ground support equipment and aircraft armament equipment are also inspected.

d. In addition, aircraft are inspected by an audit team inspector anytime an aircraft is to be transferred to another controlling custodian (COMNAVAIRPAC/COMNAV-AIRLANT). All corrosion discrepancies are corrected before the aircraft is transferred.

5 All corrosion maintenance prevention and corrective action is documented in the U. S. Navy Data Collection System. A five-year study revealed that 10% of all available aircraft maintenance labor was being expended for corrosion maintenance. A further breakdown of collected data revealed that 7% of the labor was expended on corrosion preventive actions and 3% expended on corrective action such as corrosion removal. The 10% total man-hours devoted to corrosion maintenance equates to 2,000,000 man-hours annually.

6. Corrosion is reported in accordance with requirements of Chief of Naval Operations Instruction 4790.2B reporting systems.

7. The corrosion prevention program has received great emphasis throughout the Atlantic and Pacific Fleets, and considerable progress has been made, e.g., no unsatisfactory aircraft have been reported as the result of COMNAVAIRLANT/COMNAVAIRPAC Audit Program in the past three years. This indicates no laxities on the part of squadrons in complying in the Corrosion Prevention/Control Program. (In the early and mid-1970, it was not uncommon to induct an aircraft into depot level maintenance for corrosion repair that could have been prevented. Some induction required as much as 2,000 man-hours to repair corrosion.) Today, we still see some severe corrosion; however, it is discovered primarily during rework when the aircraft is disassembled beyond the capability of the squadron level activities. These problems can generally be traced to the use of corrosion prone materials by the airframe manufacturer, inaccessibility and lack of sealant to prevent intrusion of moisture or corrosive chemicals. As noted above, there has been a marked decrease in stress corrosion cracking of high strength aluminum alloys as a result of the use in later aircraft of the new stress corrosion resistant alloys and heat treatments.

8. In order to minimize down time or loss of aircraft due to corrosion damage, direct liaison has been established between the fleet and Naval Air Development Center (NAVAIR-DEVCEN) with a daily dialogue. Now when a corrosion problem is reported by the fleet, rapid action by NAVAIRDEVCEN quite often provides the corrective course of action the same day the problem is reported.

a. When a corrosion prone material is involved, the Research and Development (R&D) community will often recommend replacement of the corrosion prone material with more suitable material for the specific accplication for repair and as placement material on later constructed aircraft, or the application of a different protective coating system to the corrosion prone area of the model aircraft.

b. This program of cooperation has also provided the R&D community with a real world environment to evaluate new material and protective systems under actual operating conditons at sea for long exposure.

c. In keeping with this program, a year ago the fleet requested NAVAIRDEVCEN to investigate the possibility of developing a non-corroding electrical connector using the new composite materials for the shell of connector, which would eliminate one of the problems discussed above. NAVAIRDEVCEN has reported good progress in the development of the non-corroding electrical connector.

9. Conclusion:

a. Corrosion damage can be minimized on aircraft and other military equipment by a dynamic, continuing corrosion prevention/control program with all hands involvement.

b. Detailed training of involved personnel must be provided.

c. Technical manuals easy to understand by the layman and maintained up-to-date with state-of-the-art procedures and materials must be available to the mechanic.

d. As new materials are developed and introduced, corrosion can be designed out of aircraft by cooperation between the aircraft design engineer, working with the material engineer and the user.

e. Closer cooperation between all facets of the aerospace community, such as the fleet/NAVAIRDEVCEN cooperation described in paragraph 8, is needed to insure that the most durable, reliable aircraft and hardware is provided to the armed forces.

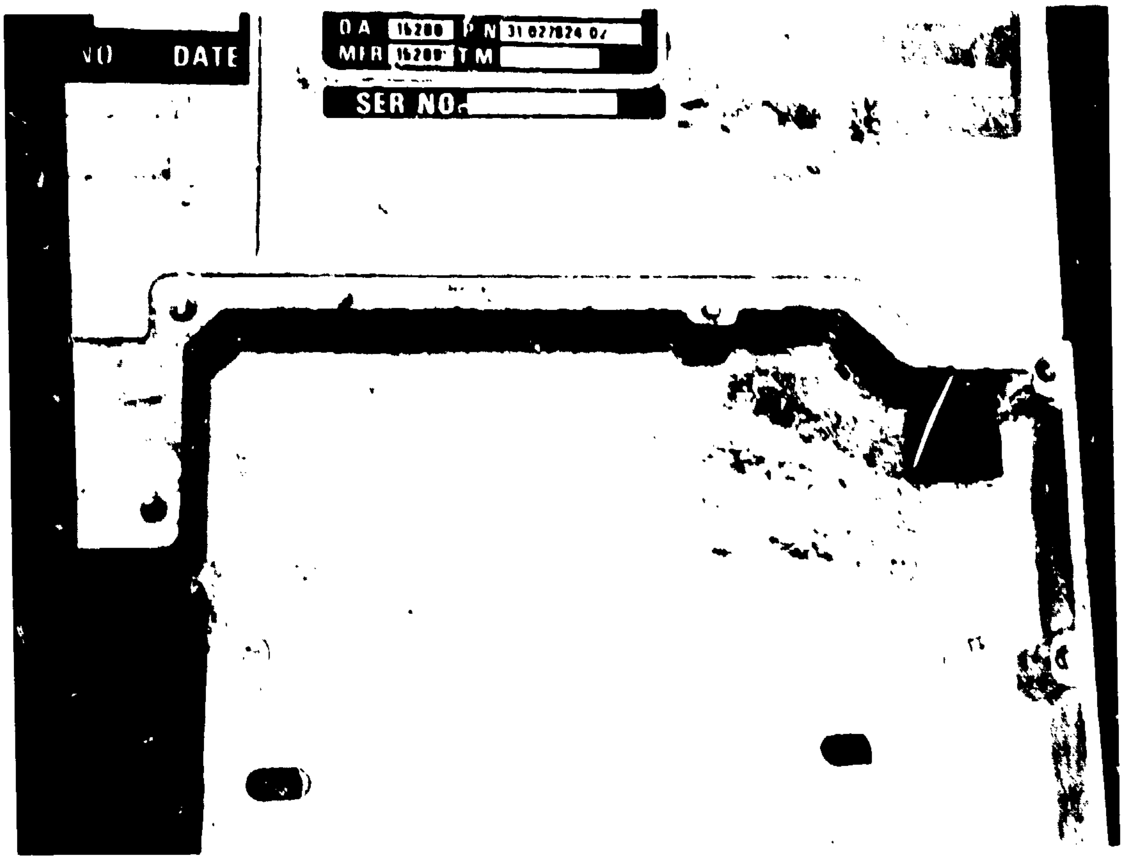


Fig.1 Corrosion on avionics lid ALR-45

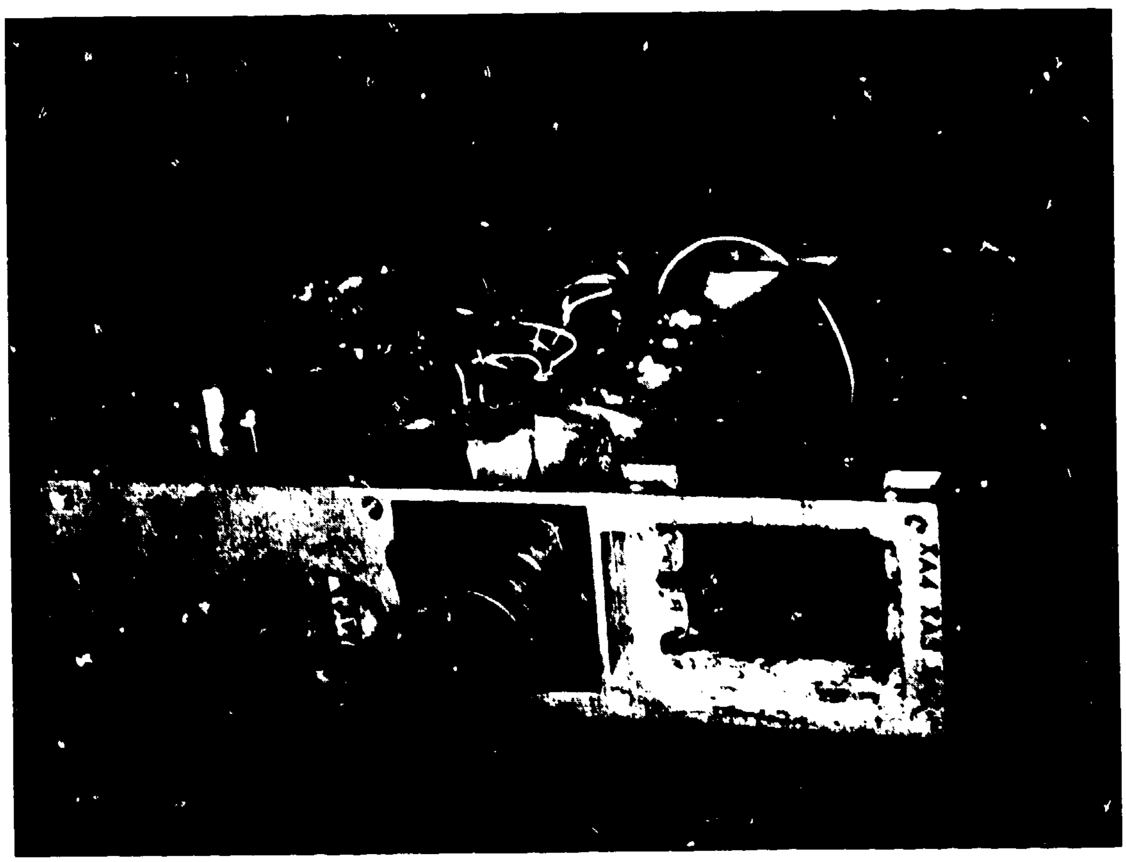


Fig.2 Corrosion inside avionic ALR-45

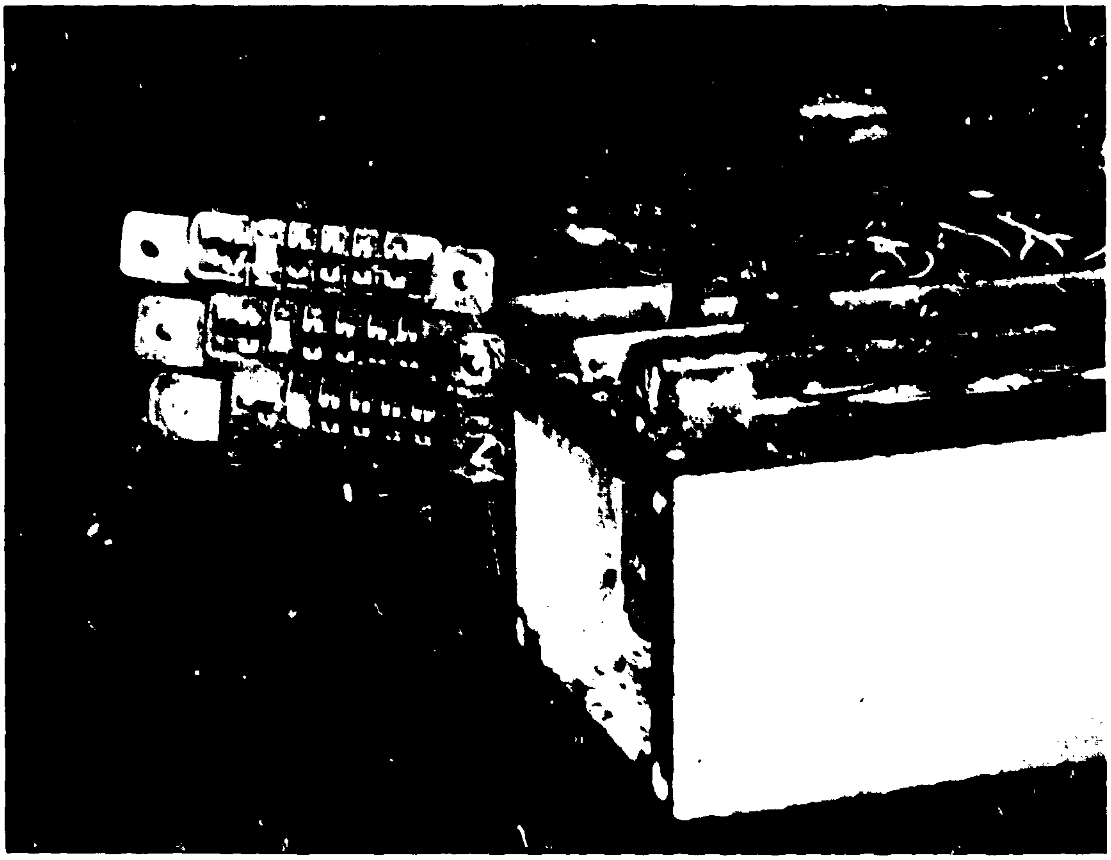


Fig.3 Corrosion inside avionic ALR-45

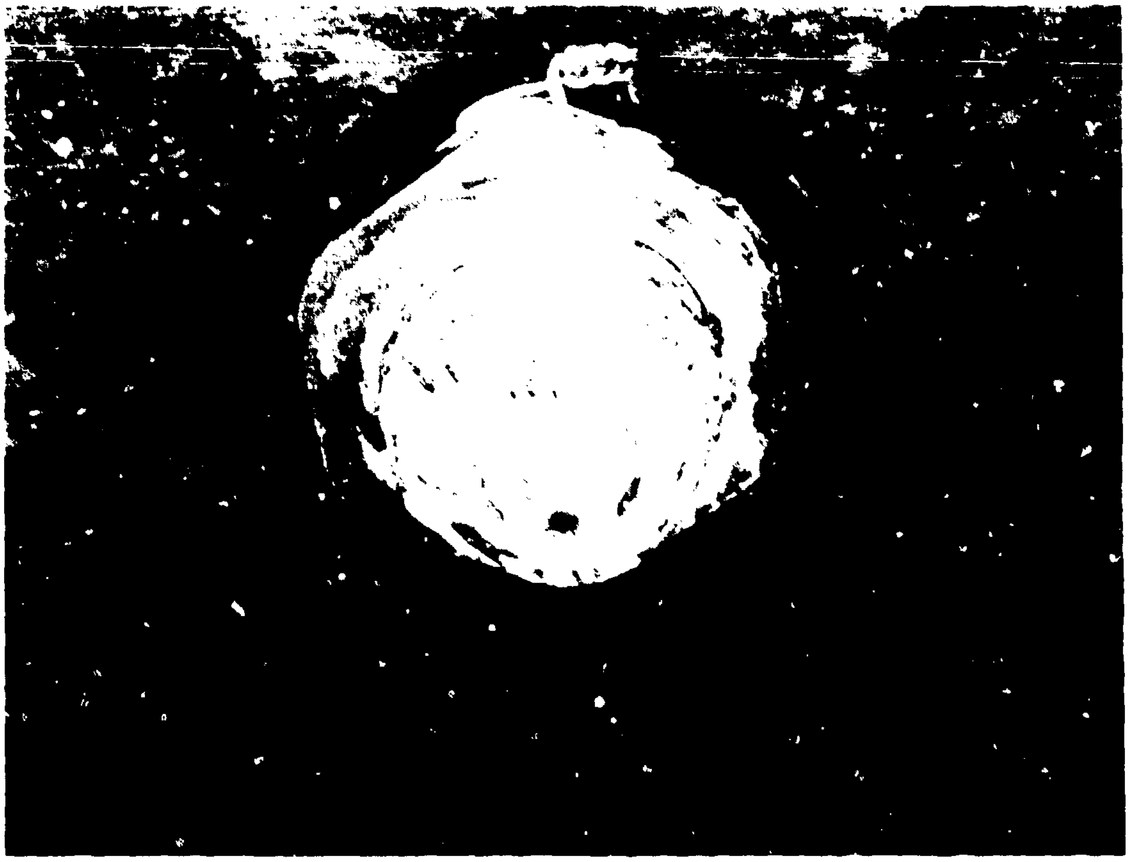


Fig.4 Corrosion avionic coaxial connector

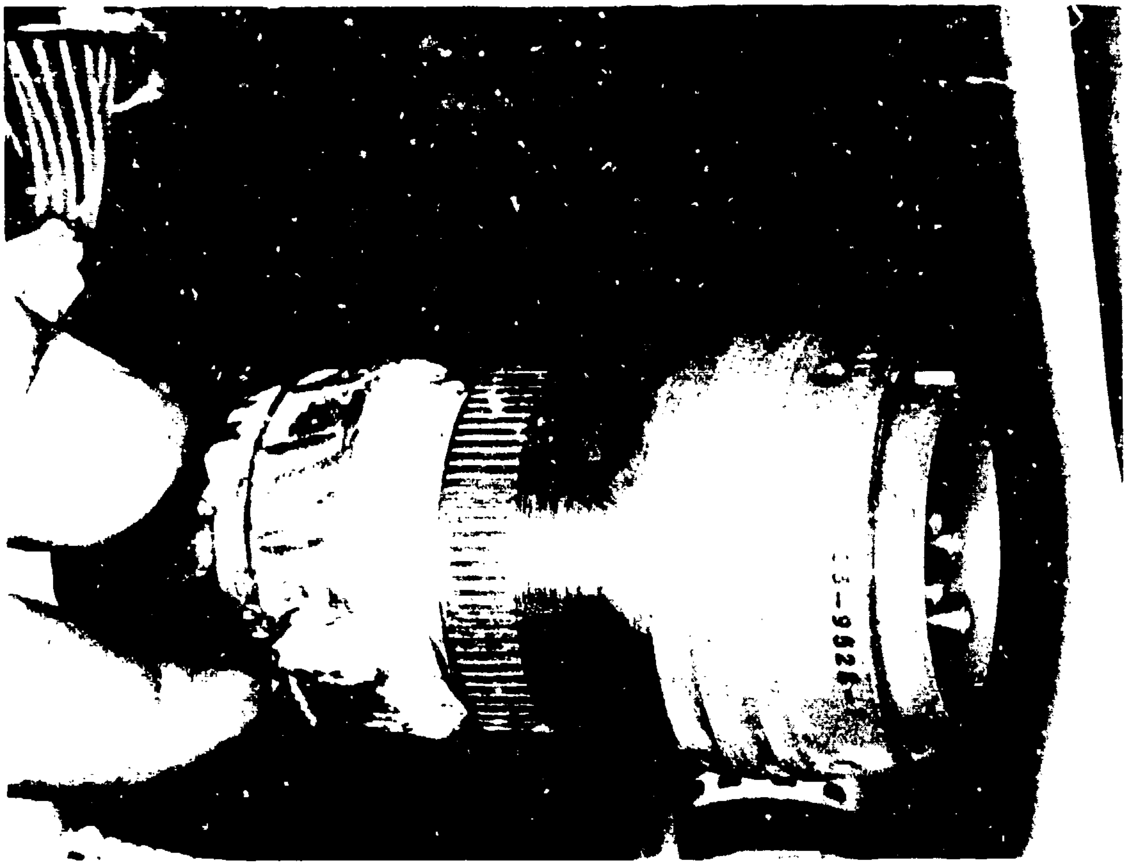


Fig.5 Corrosion of environmental connector

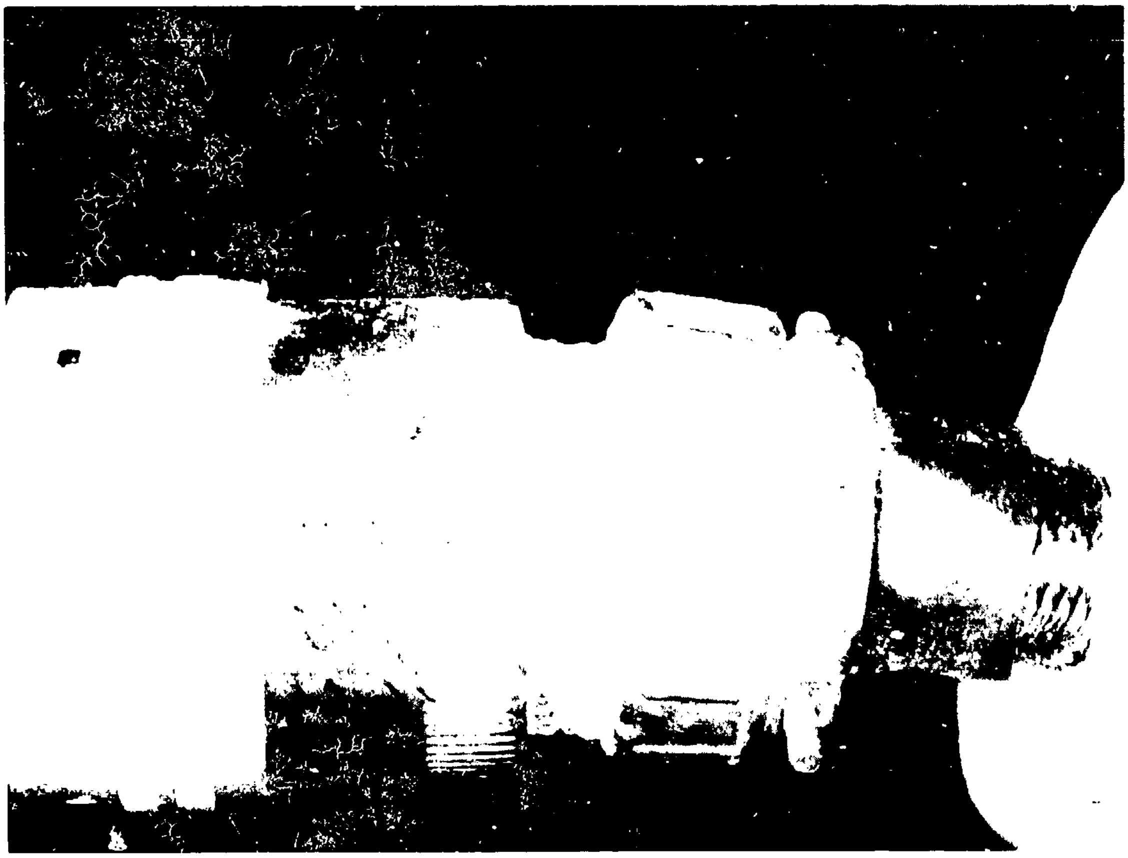


Fig.6 Corrosion of environmental connector

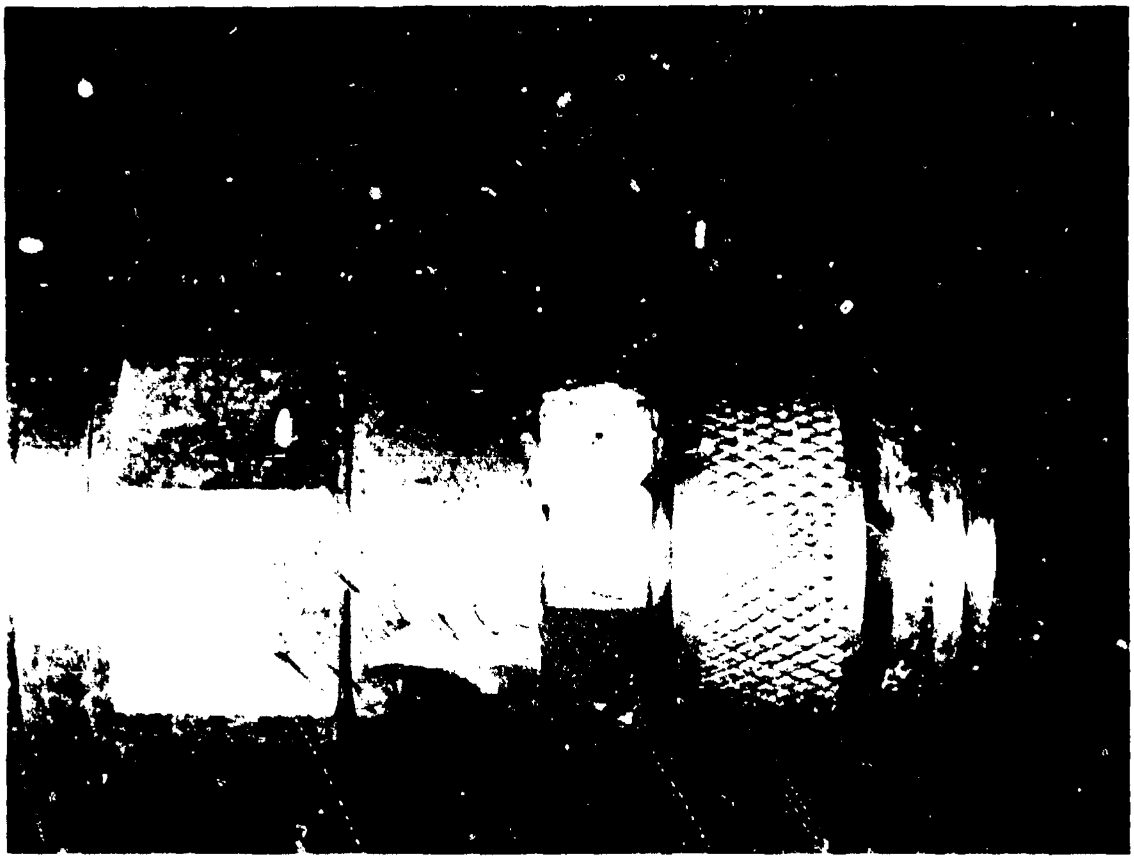


Fig.7 Corrosion of electrolus nickel plated connector

Fig.8 Corrosion of electrical motor

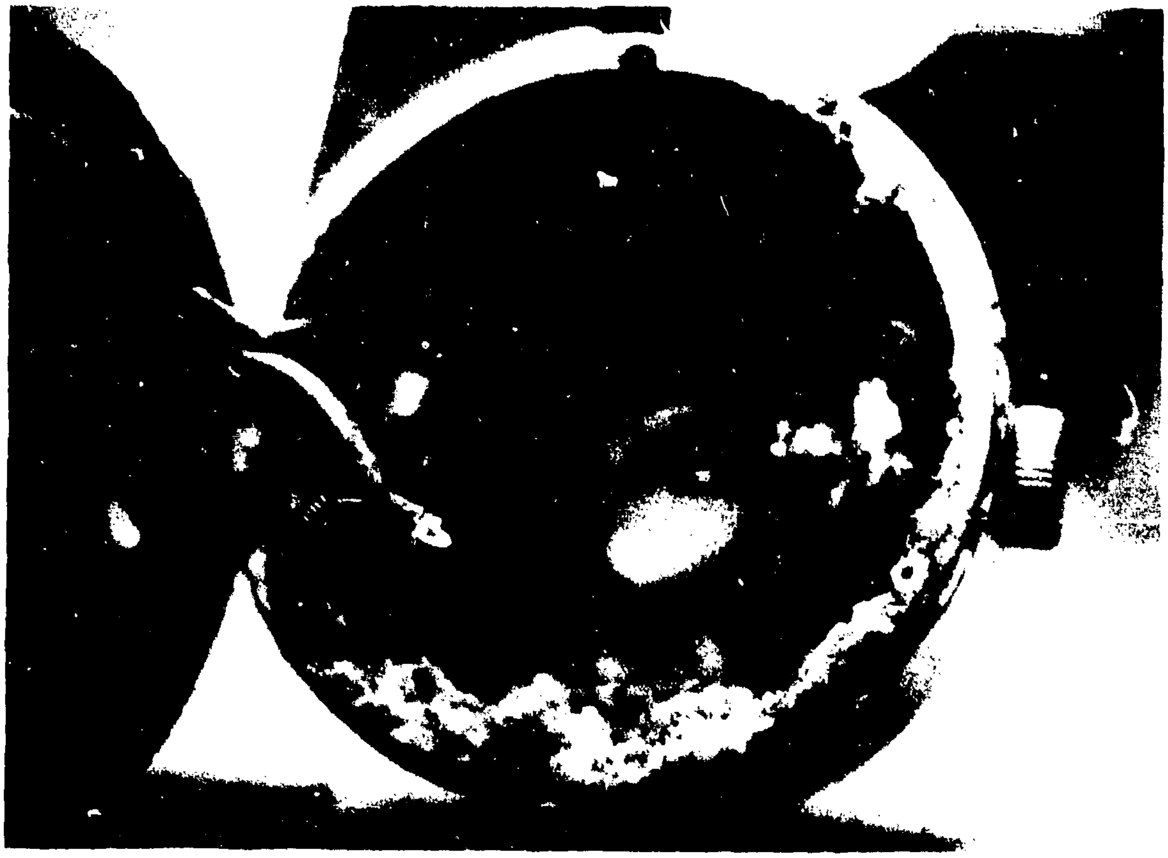


Fig.9 Electrical motor corrosion

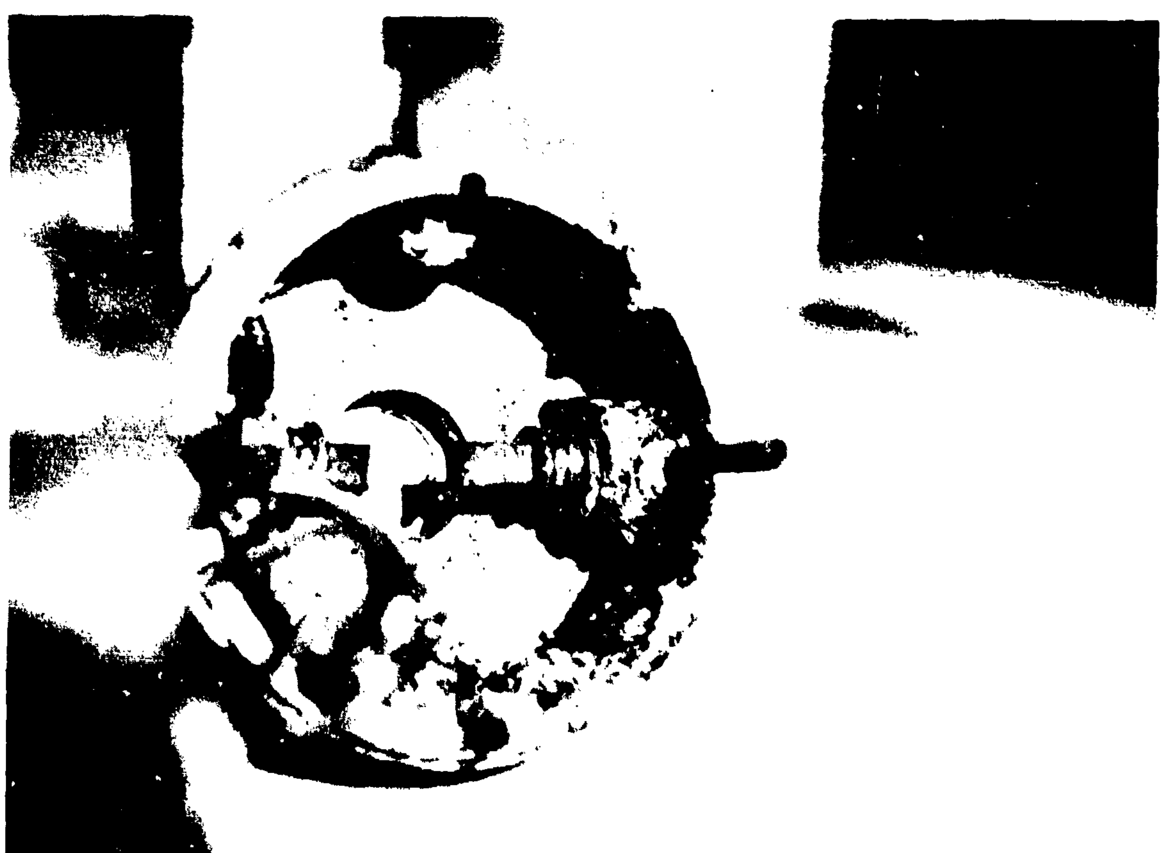


Fig.10 Electrical motor corrosion

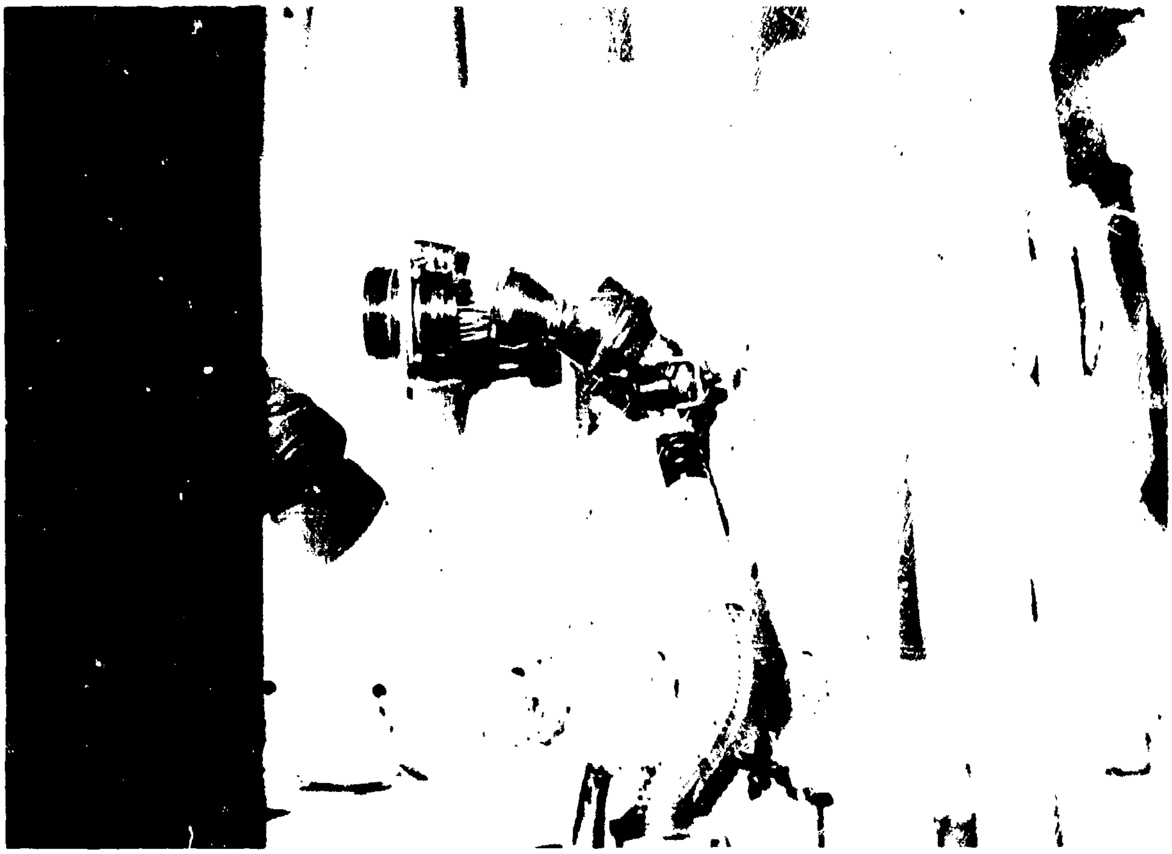


Fig.11 Sealed environmental connector after 15-month at-sea evaluation

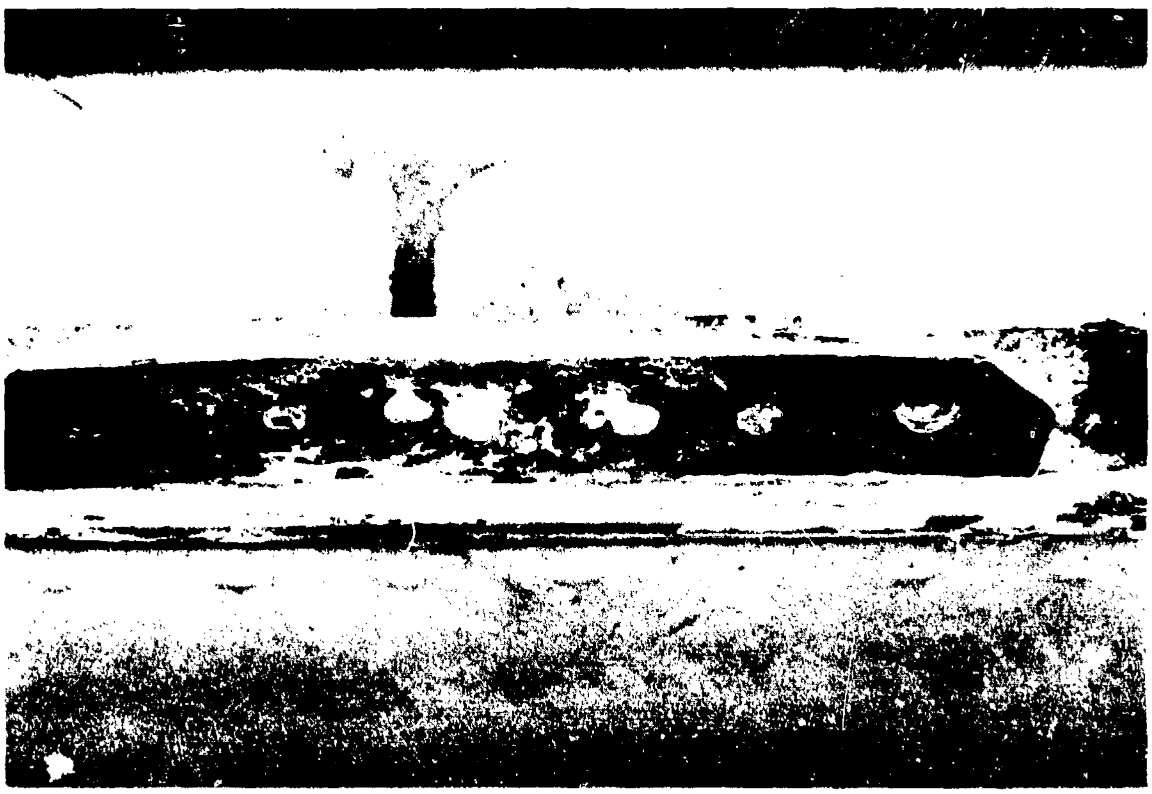


Fig.12 Corrosion caused by the use of dissimilar metal with insufficient sealant

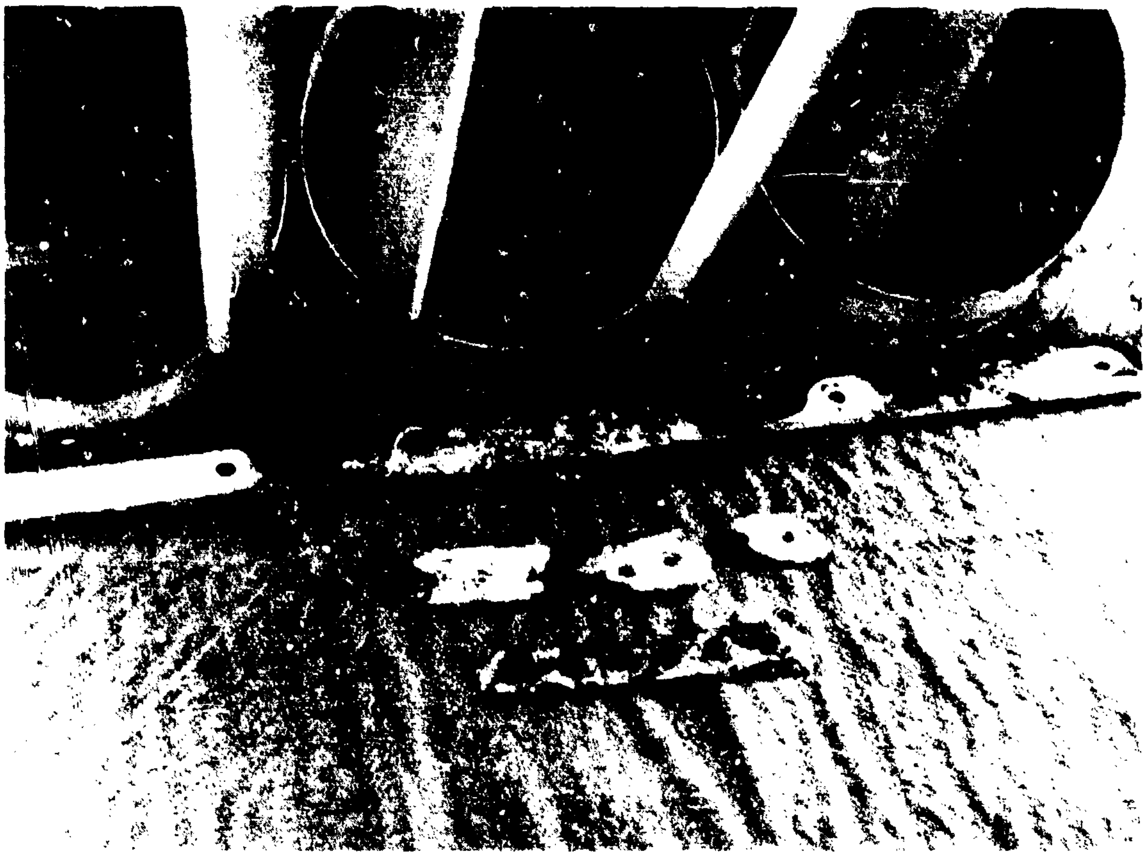


Fig.13 Corrosion caused by the use of dissimilar metal with insufficient sealant

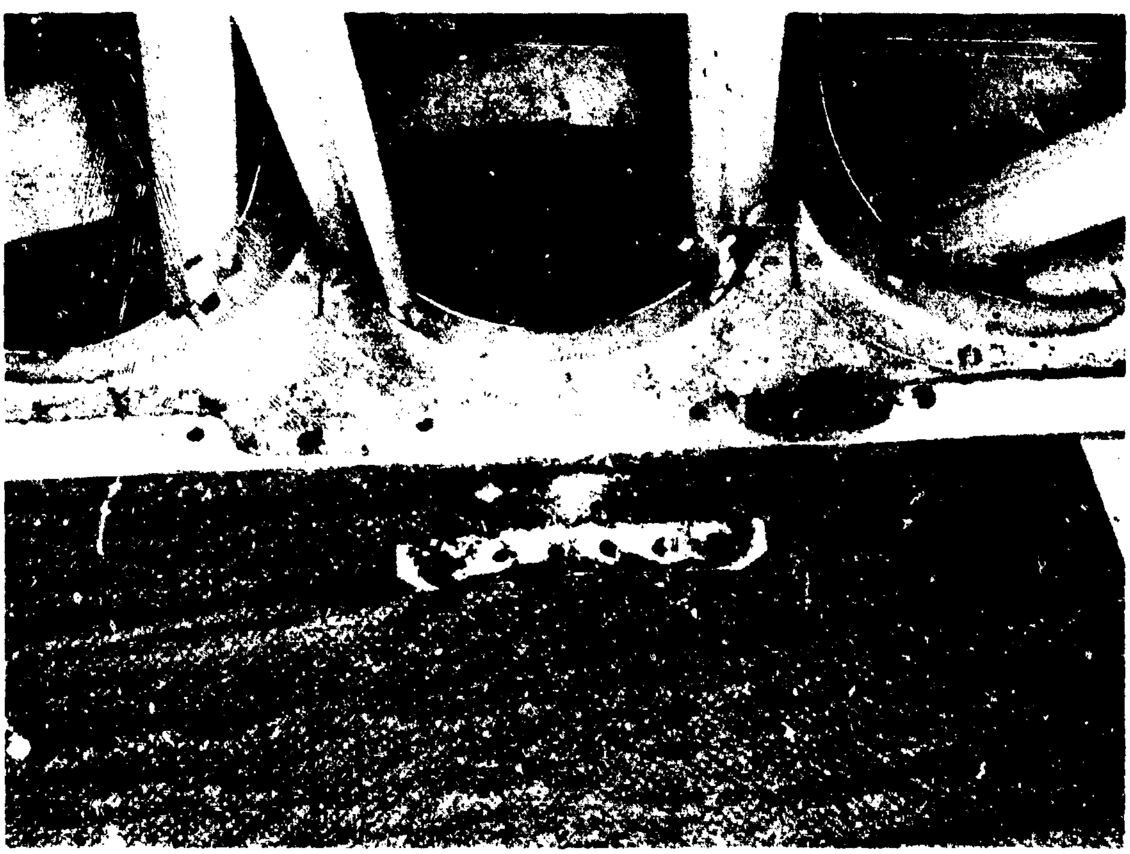


Fig.14 Corrosion caused by the use of dissimilar metal with insufficient sealant

Fig.15 Corrosion caused by the use of dissimilar metal with insufficient sealant

Fig.16 Corrosion caused by the use of dissimilar metal with insufficient sealant

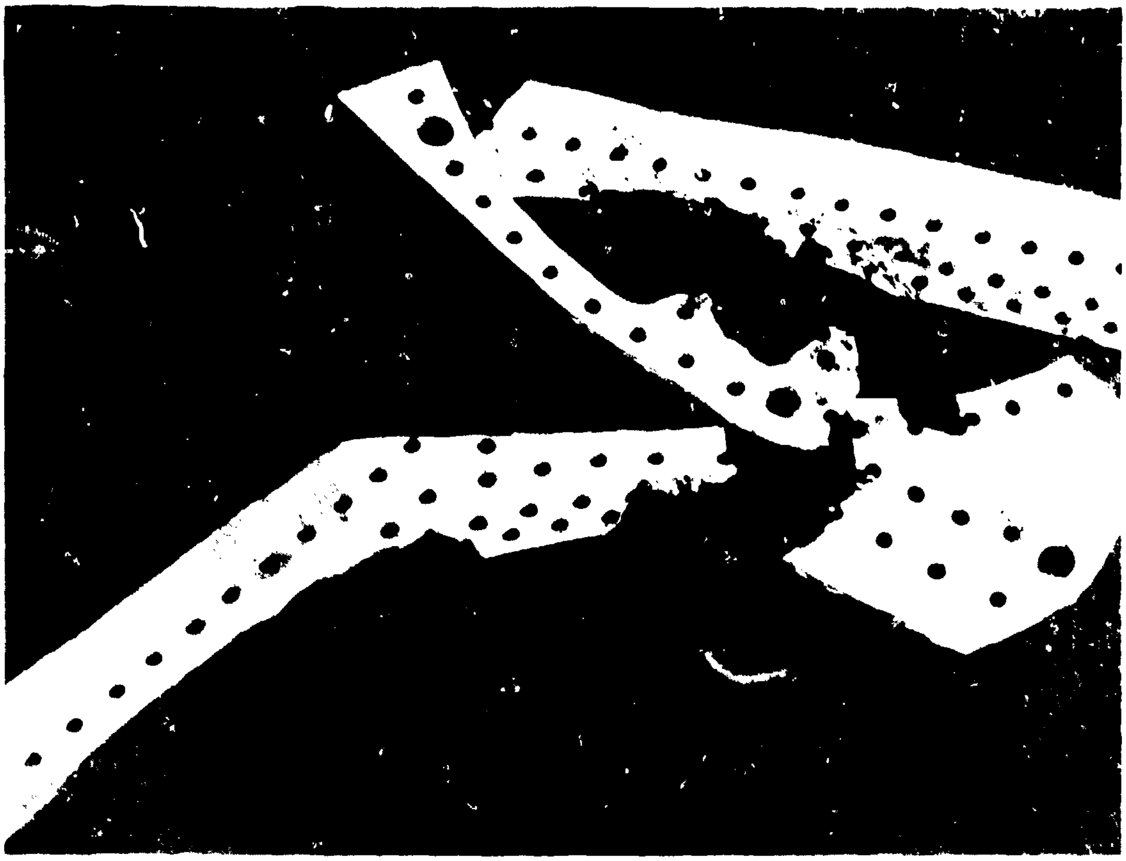


Fig.17 Improper material selected for use

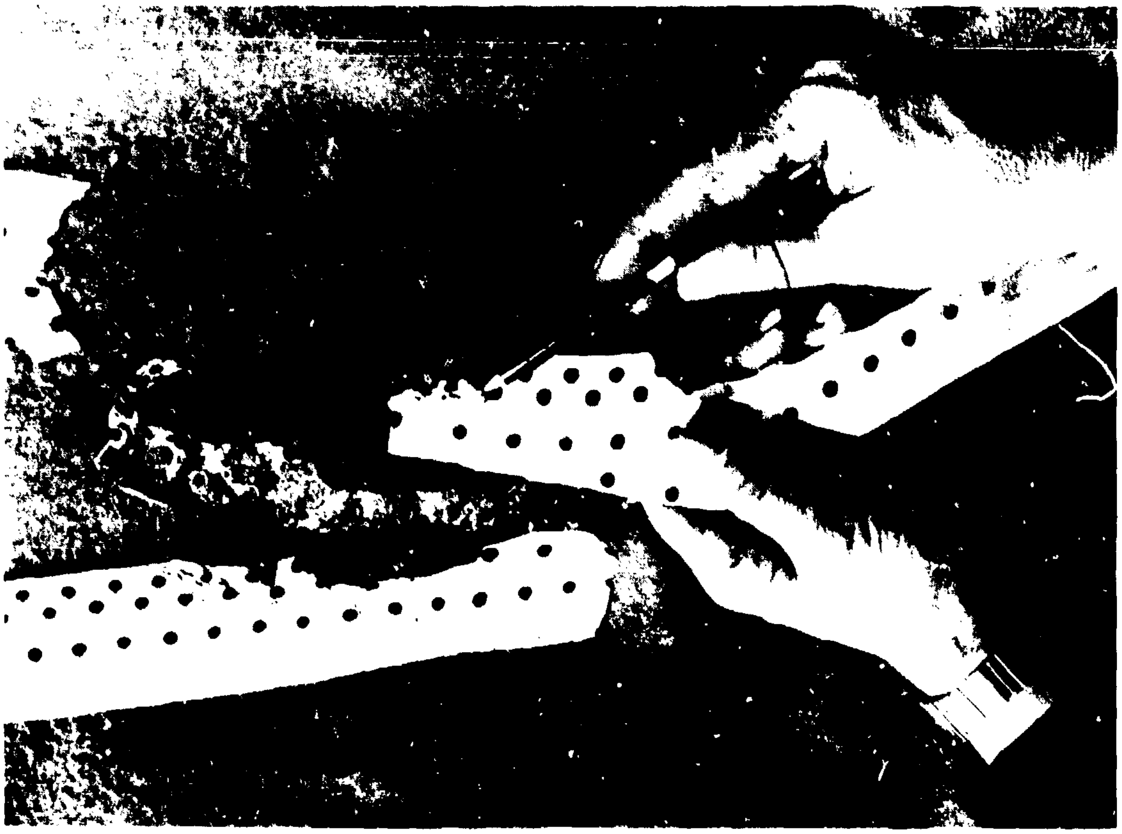


Fig.18 Improper material selected for use

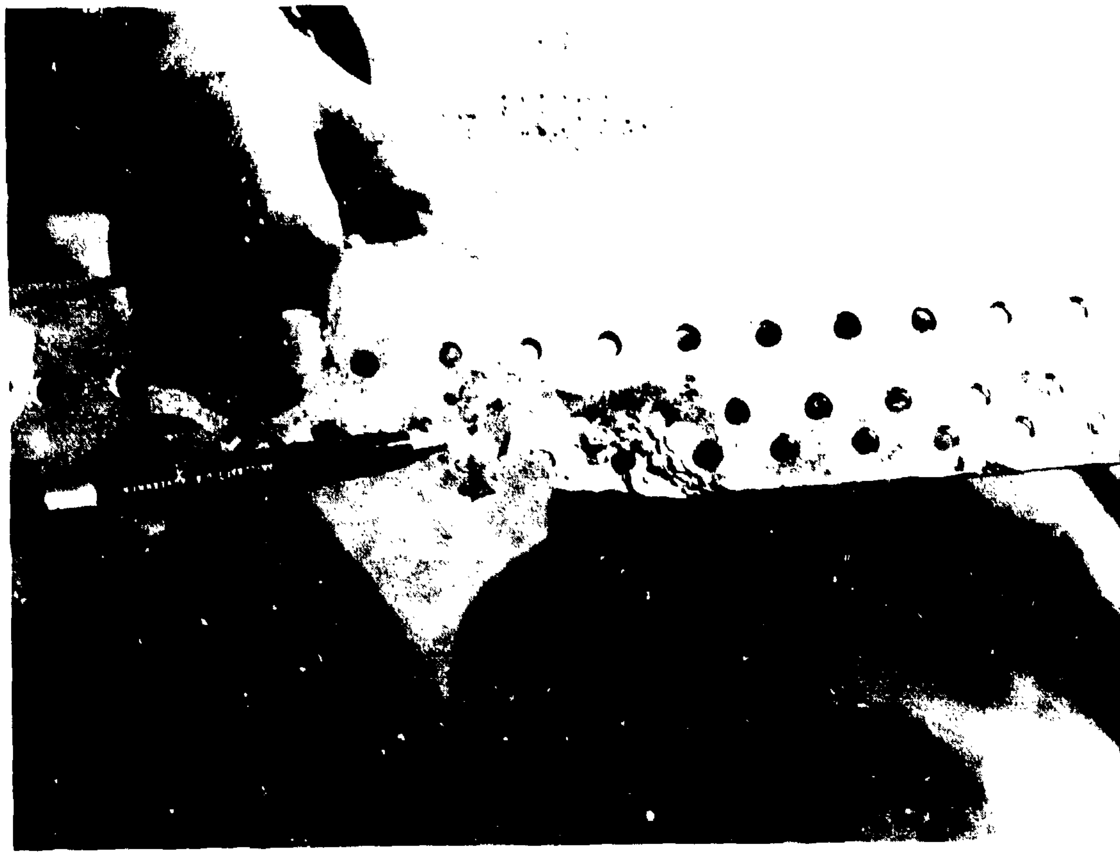


Fig.19 Improper material selected for use

Fig.20 Improper material selected for use

Fig.21 U.S. Navy operating environment

Fig.22 U.S. Navy operating environment

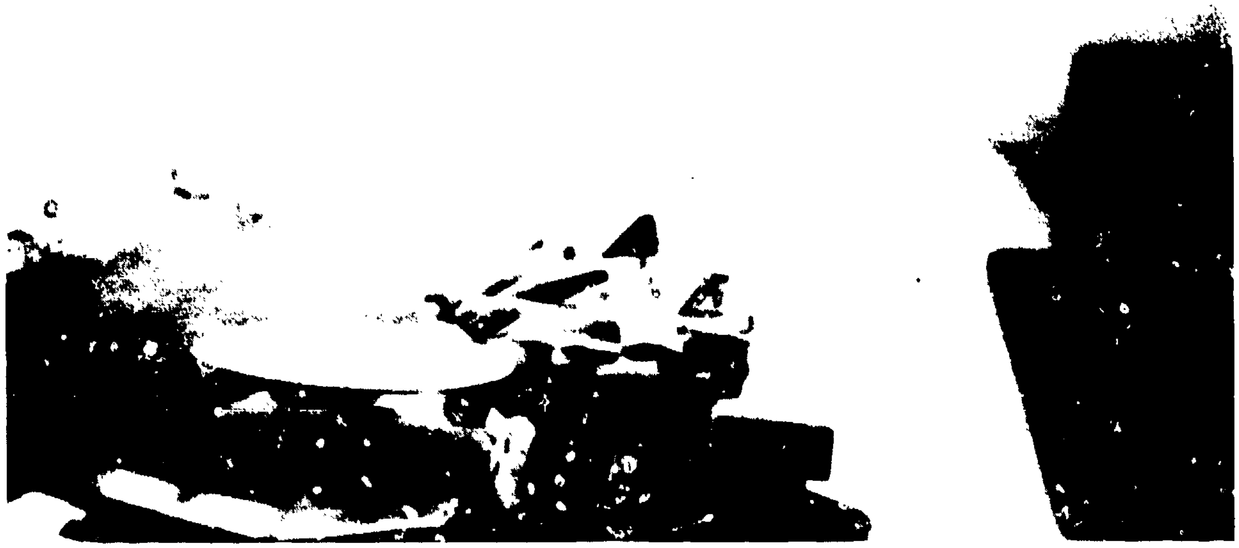


Fig.23 U.S. Navy operating environment

DETECTION AND PREVENTION OF CORROSION IN ROYAL AIR FORCE AIRCRAFT

by
C R Pye
Squadron Leader
Central Servicing and Development Establishment
Royal Air Force
Swanton Morley
Dereham
Norfolk
NR20 4LJ
Great Britain

SUMMARY

This paper outlines, with an example, the problems that sometimes are created by corrosion in Royal Air Force aircraft. It describes the problem of the harsh environment facing some military aircraft and touches on some of the materials used in aircraft construction. The Royal Air Force's policy for corrosion prevention and rectification is also discussed briefly.

The paper illustrates some typical examples of corrosion damage found during service and describes the non-destructive testing methods used for detecting corrosion. These methods include visual inspection, eddy current techniques, ultrasonic techniques and X-radiography. Comment is also made on the use of neutron radiography and other future developments. Service methods of removing corrosion and re-protecting the aircraft are mentioned. Finally the need for the manufacturer to consider corrosion at the aircraft design stage is considered.

INTRODUCTION

1. The two prime aims of the aircraft maintenance engineers in the Royal Air Force are:

   a. To ensure that aircraft life cycle costs are kept to a minimum.

   b. To give the operator maximum aircraft availability commensurate with safety.

At present, corrosion is an aircraft defect that prevents us from achieving both aims. We spend many manhours both removing corrosion and replacing corroded components at a large cost in both labour and spare parts. Elapsed times for repairs are long, often because each individual rectification job can only be undertaken by one or two men, and consequently aircraft availability is adversely affected.

2. Figure 1 presents how the RAF sees corrosion and is the basis for the discussion in the report. At the top of the figure the RAF formulates its requirements for an aircraft. These requirements are then turned into an aircraft design by an aircraft manufacturer. The designed aircraft enters service and immediately starts to corrode. At this stage, we do not know whether the corrosion will take many years or even the life of the aircraft to manifest itself or whether it will become a problem in 2 or 3 years of operation. We now enter a complete block of the Figure which has been entitled Prevention of Corrosion. This block is based on the assumption that in the long term it is cheaper to prevent corrosion rather than to allow it to occur, and then have to undertake extensive costly repairs. In the RAF the important elements of corrosion prevention are policy directives,education of the tradesmen, paints and protective treatments, corrosion control teams, first aid kits and aircraft washing. We monitor the success of our corrosion prevention measures by structural examinations, the results of which are recorded. If our programme of prevention is unsuccessful we enter the next block of the Figure entitled Rectification of Corrosion. Here we use special non-destructive testing techniques to detect corrosion in areas where we know it is likely to occur. Again we stress the importance of the education of the tradesmen in recognising significant corrosion. Once we have detected significant corrosion we need effective ways of removing it. We find that removing corrosion is invariably cheaper than replacing the corroded component. We then require effective reprotection methods otherwise we will be faced with the same corrosion in another period of time (which is all too often the case). On completion of our corrosion rectification we again record our findings. Recording at both stages in the cycle is used as feed back to shape our future requirements and is also available to the aircraft designer. For the Nimrod aircraft we have started to measure the effectiveness of the programme by finding the costs of prevention and comparing these with the cost of cure. This effectiveness should be used to shape future policies and the other preventive measures.

THE PROBLEM

3. In the RAF we have made several studies into the costs of aircraft corrosion. The actual costs are exceptionally difficult to quantify and require a lot of effort to gather. The rectification costs of each individual aircraft type vary greatly as illustrated by the league table in Figure 2. This Figure presents an estimate of corrosion maintenance costs per active aircraft relative to the cheapest aircraft to maintain for corrosion alone. The figure shows three underlying trend factors that determine corrosion maintenance costs. These are the size of aircraft, the age of aircraft and the environment of operations. There does not appear to be any way of relating the factors together; one of the three factors can dominate the other two for one particular aircraft type. Another very important factor that becomes apparent when the defect data is analysed is the construction of the aircraft. The use of corrosion prone materials such as magnesium alloys, or the lack of proper corrosion protection on assembly such as dry assembly, can drive the corrosion cost-factor up considerably. These factors are based on corrosion rectification costs, that is to say, costs that are incurred after corrosion has been discovered. In addition to these costs the RAF also considers the costs of corrosion prevention. Corrosion prevention costs include

restoring surface finish, washing and special examinations specifically for corrosion.

4. To analyse the costs of corrosion further we have studied the Nimrod maritime patrol aircraft which is the costliest aircraft in terms of corrosion, in the RAF. However, at the same time we recognise that the Nimrod was constructed out of materials that were available in the 1950s and consequently it would not be typical of aircraft designed and made now. Nevertheless, we are likely to have to live with the Nimrod for many years yet. In a typical year the costs of corrosion rectification per Nimrod aircraft are substantial but it is equally interesting to know that the costs of corrosion prevention are 1.6 times higher. All the corrosion work is generally concentrated at major servicings which occur at approximately 4 yearly intervals and the average elapsed time on each major servicing for work directly attributable to corrosion is generally 1/3 of the elapsed time for the whole major servicing. Corrosion therefore reduces aircraft availability. This reduction in availability is a more significant cost than yearly manhours if there is a need to buy extra aircraft to cover further down time due to corrosion. The reduced availability costs are about twice the manhour costs directly attributable to corrosion. Corrosion of aircraft structure is generally the only form of corrosion considered because it is the highest manhour consumer and because it poses a serious threat to structural integrity. However, corrosion of systems and non-structural components can also be significant as illustrated by the comparison in Figure 3, which lists corrosion rectification costs in descending order of importance. In addition to the costs already indicated some proportion of the costs of most structural inspection must be attributed to corrosion. However, it would be unfair to apportion a percentage of these inspection costs to corrosion because the inspections would still be necessary for fatigue cracks and other forms of damage, even if corrosion did not exist.

5. Returning to the four factors that appear to determine corrosion maintenance costs ie aircraft size, age, environment and construction. Then perhaps size and age can be dismissed without any discussion because size determines the amount of structure (and often the complexity) to inspect, corrode and repair and because everyone knows that corrosion is an age related failure. Environment, however, is a less quantifiable factor which appears to often readily dominate at least size and age. The RAF's Nimrod aircraft is a derivative of the Comet airliner which was also in service with the RAF as a transport aircraft. The change of environment, from flight at high level to flights often at very low altitudes above the sea for long periods of time, has had a dramatic effect in increasing the amount of corrosion on each aircraft. The environment has completely dominated any age effect as illustrated by Figure 4 where age of aircraft has been plotted against rectification costs for a year. There does not appear to be any correlation between age and corrosion rectification costs. However, there could be one further influence that is not immediately obvious and that is knowledge, experience and awareness. We find that, as our knowledge and awareness of an aircraft grows from the in-service date, we know where to look for corrosion and therefore we are more likely to find it. Environment has also dominated size for maritime helicopters which are comparatively small but come high up the corrosion league of Figure 2.

6. Construction was the last factor which determined an aircraft's rate of susceptability to corrosion. All the defect data we have points to the fact that corrosion costs on all aircraft are to a large extent determined by a limited number of areas on that aircraft. Significant corrosion never occurs all over an aircraft. There is usually a prime cause for the corrosion in every area. The most common cause is the poor corrosion resistance of the construction material. Materials have their own degree of corrosion resistance which can be improved by surface treatments and protective finishes. Moreover, they have different electrical potentials when adjacent to different materials. Nevertheless some materials are corrosion prone no matter what protective measures are taken. Magnesium alloys are probably the most corrosion prone structural materials used in recent years in RAF aircraft. The corrosion resistance of the aluminium-zinc alloys used in the Nimrod has been poor. In addition to corrosion being the result of basic material problems,corrosion is often due to a local hostile environment which is attributable to the aircraft's construction. Corrosion in toilet and galley areas is generally a problem. Replacement of a toilet floor, which in itself is often a simple structural item, can be a major repair. Other typical examples of local hostile environments are seat rails adjacent to cabin doors and battery stowage areas.

RAF POLICY

7. The RAF combats corrosion with a programme of regular examination, rectification of damage and reprotection for all its aircraft. In addition washing of aircraft is undertaken at specified intervals. RAF policy is that as much structure as possible is examined on all aircraft. However, where there is a large manhour penalty in examining a particular area, the assumed condition of the area is based on a sample of the fleet only. In general, all the inspections are carried out at the major servicing which occurs for most aircraft after every 3 to 4 years of operation. The surface finish will also be restored at the major servicing. Between major servicings, corrosion prevention, detection and rectification is more restricted. Minor servicings, after 300 to 400 flying hours, are carried out in hangars where there is a good engineering environment for corrosion detection, either for rectification or containment, and for application of preventative measures. To tackle the corrosion problems on the Nimrod the RAF has introduced Anti-Deterioration Servicings on a calendar cycle basis as part of a major preventative campaign. During these servicings certain areas are sprayed with water dispersing corrosion inhibiting fluid. Also as part of the same campaign, corrosion control teams have been introduced at Nimrod units to carry out a systematic programme of inspection and rectification aimed at preventing any outbreaks of corrosion developing into more serious damage. These teams are full time autonomous teams and tackle aircraft on a random basis as permitted by normal down time due to rectification of other defects.

8. By having corrosion control teams we aim to build up expertise and experience of corrosion and thereby combat corrosion more effectively. The Senior Non-Commissioned Officer in charge of each team undertakes a 2 week course on corrosion control and is awarded a corrosion control qualification. The RAF believes that good training and high motivation in tradesmen are essential requirements in combating corrosion. It is important to teach each airframe tradesman the importance of finding corrosion and the need for its timely removal and the reprotection of the area affected. We have a comprehensive corrosion manual which is intended for the corrosion specialist and a corrosion pamphlet which is intended to tell every airframe tradesman the basics of corrosion. The corrosion pamphlet is widely distributed to airframe tradesmen and especially during their initial training. Additionally, we try to keep tradesmen continuously aware of

corrosion by posters and by a training film which has recently been produced.

PAINT SCHEMES AND PROTECTIVE TREATMENTS

9. Until recently the RAF used polyurethane paints to finish its aircraft. However, all aircraft except the Nimrod and VC10 are changing over to acrylic paints. The main reason for the change was the relative ease at which acrylic paint could be selectively stripped when compared to polyurethane paint which we could find no safe way of removing. Polyurethane paints had to be continued for the Nimrod and VC10 aircraft because of the paint's resistance to the highly corrosive fire resistant hydraulic oils used in those aircraft. There was no clear division between the two paint schemes for their corrosion resistance. Polyurethane paint was thought to be too brittle and found to crack around fastener heads whilst acrylic paint was known to be prone to microcrazing. For either scheme the need to apply the paint under the correct conditions is fundamental for good corrosion resistance. We have been trying more flexible polyurethane paints on the Nimrod and have now found a paint which has sufficient adhesive and erosion resistant properties and is less prone to cracking around fastener heads. As another part of our active programmeof corrosion prevention the RAF introduced a First Aid Anti-Corrosion Kit which included all the tools and materials necessary to restore small areas of surface finish on an aircraft. The kit is shown in Figure 5. It is used at first line for reprotecting minor damage on a temporary basis. The damage is later permanently reprotected under better conditions.

10. The RAF currently uses 2 types of temporary protective in selected locations on some aircraft to supplement the protection given by the paint finish. The first fluid, known as PX-24 (specification equivalent to Ardrox 3961, WD40 and LPS3) is a water displacing fluid which leaves a protective film. This is used mainly after washing and gives only very short-term protection. However, there is some evidence in the UK that PX-24 adversely affects the fatigue life of some rivetted joints and consequently, we only use PX-24 on RAF aircraft after considering possible fatigue implications. The second type of temporary protective is known as PX-28 (specification met by Croda Plaswax and in most respects by Ardrox 3302). This is a heavier, thick wax-based corrosion inhibiting compound originally developed for protecting road vehicles. It is applied by brush or airless spray and is particularly suitable for treating enclosed sections of structure. The compound gives protection for up to 6 years. It is a brown grease-like substance as supplied. Its thickness, colour and attraction for general dirt make it likely to hide structural damage; moreover, it is not very resistant to temperature changes and it is not easy to remove for more detailed inspection of the structure underneath. Nevertheless, we believe it to be worthwhile and specify PX-28 application where additional protection is necessary. PX-32 is a specification for a new corrosion inhibitor specifically developed for aircraft use. It will have a much thinner coat than PX-28, be more translucent, easier to strip and it will not attract dirt so readily. We hope to introduce a PX-32 material in the future as a substitute for PX-28. At the moment the RAF is looking into any fatigue penalties that PX-32 might produce in rivetted joints by testing products which meet the PX-32 specification.

AIRCRAFT WASHING

11. The majority of RAF aircraft are generally washed with water and detergent solution after about 100 flying hours and additionally before minor and major servicings. The Nimrod and other marine environment aircraft are washed more frequently. RAF Kinloss which is one Nimrod base has a freshwater spray system built into one taxiway. The aircraft taxi through the spray on returning from a low level sortie over the sea and thereby wash the salt from the external surfaces of the aircraft. Maritime helicopters are hosed down with fresh water daily after flying over the sea. Nevertheless, although we are convinced of the need for regular water detergent washes to keep the aircraft clean, we are not totally convinced of the benefits of frequent water washes for maritime aircraft. Opinion is divided as to whether fresh water washing forces water and salt into the areas of the aircraft which would otherwise remain dry, and thus increases the risk of corrosion. There appears to be no correlation between the amount of corrosion on Nimrod aircraft that have regular fresh water washes and those that do not. Figures 6 and 7 show from RAF experience corrosion prone areas on a transport type aircraft and a helicopter type aircraft respectively. The individual areas illustrated are not exhaustive because corrosion will occur anywhere where the design against it is inadequate.

DETECTION OF CORROSION

12. The RAF uses a number of methods to look for corrosion in aircraft and aircraft structure in particular. These methods are visual examination, aided visual examination, eddy currents, ultrasonics and x-radiography. Each method has limitations in how and where it can be applied. Methods other than visual inspection are rarely used as a general search technique. They are only used for specific areas where visual inspection has been shown to be totally inadequate or where corrosion is known to be a problem.

13. Visual Examination. Visual examination by airframe tradesmen is the principle method of examination employed for corrosion detection at the regular scheduled inspections and during unscheduled rectification. However visual examination is limited to the areas of the aircraft which can be readily seen, that is to say, the external surface and those internal areas which can be made accessible by the removal of access panels and equipment. Even then examination may be restricted by the use of paints, protective treatments and sealants and in areas where corrosion is known to occur consideration will be given to the removal of protective layers, other than paint, to facilitate proper inspection. Paint will only be removed when its adhesion can be seen to be poor or there are signs (eg pinholes) of corrosion underneath it. We can see no justification for the removal of sound paint for anti-corrosion inspections. Where structure is enclosed or inaccessible aided visual examination using mirrors, endoprobes and fibrescopes will be considered. The RAF has found these aids very useful in extending the area of accessible structure of modern aircraft, and on some in-service aircraft we have been incorporating more small inspection holes to give access to internal structure. However, the eye is still defeated by the problem of detecting corrosion within laminated structures, especially honeycomb sandwich panels, and other structure into which access is impractical or uneconomical. Here consideration is given to use of more

sophisticated Non-Destructive Testing Techniques. These techniques are formulated for each individual inspection and carried out by specially trained and experienced technicians who form a separate Non-Destructive Testing sub-specialisation within the RAF.

14. Eddy Current Examinations. The RAF currently uses two portable Eddy Current sets which have hand held probes. These sets are the Novalec 96 and the Alcoprobe S. The Alcoprobe machine is a variable frequency set (1 MHz to 10 Hz) and is used for looking for corrosion on the inaccessible sides of thin structures. Laminated structures up to 15mm can be examined for a minimum 2% loss of material due to corrosion. However, Eddy current techniques are limited to non-ferrous materials. Their capability is further limited by edge effects, ferrous, mass and geometric effects, the variation of air gap between the laminations, paint finish and surface roughness.

15. Ultrasonic Examinations. Ultrasonic inspections can only detect corrosion in the first layer of material. Again the RAF currently uses two portable ultrasonic sets which have hand held probes. These sets are the Ultrasonic Flaw Detector and the Ultrasonic Thickness Tester. They operate in the range 5 to 10 MHz and the Ultrasonic Thickness Tester presents a digital display of material thickness and is easy to interpret. However, because the presence of liquids and corrosion products can produce results which are difficult to interpret, ultrasonic examination for corrosion is little used. It seems to have most success when directed against exfoliation corrosion.

16. X-Radiography. The RAF uses several types of portable X-ray tubes up to 150KV. X-radiography is suitable for detecting internal corrosion of light structure, skins, stringers, frames and especially closed section members. In ideal conditions a 2% reduction in material thickness can be detected by using a stepped comparator block of the same material thickness. However, conditions are rarely ideal and it is always difficult to interpret the results. Varying paint thicknesses, uneven sealant or bonding materials impede accurate results, and furthermore, the presence of corrosion products may result in corrosion remaining undetected. Unless the X-ray beam can be directed along the plane of delamination it will not detect exfoliation corrosion.

17. Neutron Radiography. The RAF conducted a trial into the use of neutron radiography for detecting corrosion in aircraft. A Californium 252 source was used and radiographs of aircraft components and a Nimrod aircraft were taken. There were no fundamental reasons why neutron radiography could not be used to detect corrosion. The tests generally showed that neutron radiography was good at detecting corrosion even in very thick structure and would provide adequate sensitivity. However, the use of Californian 252 as a neutron source was thought to be highly impracticable because of long exposure times, lack of real portability, high source cost and the associated safety measures. Moreover, we were not convinced of a specific requirement for neutron radiography especially as we failed to find any specific applications for the method even on the Nimrod. At the moment, therefore, the application of neutron radiography for detection of corrosion in RAF aircraft is not being pursued further.

18. Other Non-Destructive Testing Methods. The RAF is aware of the use of acoustic emission techniques for detecting corrosion. However, we have not yet been convinced of their usefulness or superiority to other existing methods. In the demonstrations we have attended, a lot of local heat has had to be applied to make the corrosion sufficiently active to be discernable. We are therefore only continuing to watch developments in this area. Another technique which could have future applications is where the structure is vibrated with a low power sound source and then monitored for its resonant sound signatures at various locations. At the moment however, we believe that the development of eddy current techniques offers the most likely gains in the near future. We hope to replace more and more X-ray techniques for corrosion detection with eddy current techniques. We are aware that methods of detecting corrosion have generally resulted from the methods developed to detect fatigue cracks (and have always taken second place) but we are reasonably content with this approach because the RAF has never lost an aircraft because of a corrosion failure.

CORROSION RECTIFICATION

19. Once significant corrosion has been discovered it is rectified by either removing it or replacing the corroded part. For structural items removal by cleaning pads, abrasive paper, flap wheels, conventional and rubber matrix gri... g wheels or abrasive blasting is preferred, because of cost, to component replacement. Component replacement will only be undertaken for systems components or for structural components where the depth of removal would significantly affect component strength or stiffness. Acceptable limits of material removal are often specified in our aircraft servicing manuals. Where limits are not specified or where the depth of removal is beyond the specified limits advice from the aircraft's Design Authority is sought. The RAF's quickest and most effective method of removing corrosion is the Vacublast machine which is an abrasive blasting machine with an integral vacuum system of abrasive recovery. Both glass beads and alumina grit are used as blasting media. Glass beads supposedly remove the brittle corrosion products leaving a clean metal surface. Alumina grit removes corrosion products and parent metal and consequently needs careful control. In the past, the RAF has preferred the use of glass beads because they do not remove the parent metal. However, there is now some evidence that corrosion re-occurs more frequently on sites that have been glass bead blasted because of the peening effect of the beads trapping corrosion products under the apparently sound metal surface. When corrosion has been removed or the component replaced the area is reprotected. In areas where corrosion is known to re-occur then further protectives like PX-24 and PX-28 will be considered in addition to the original paint finish or treatment. Without additional protection it is inevitable, given time, that corrosion will re-occur again in the same area.

THE FUTURE

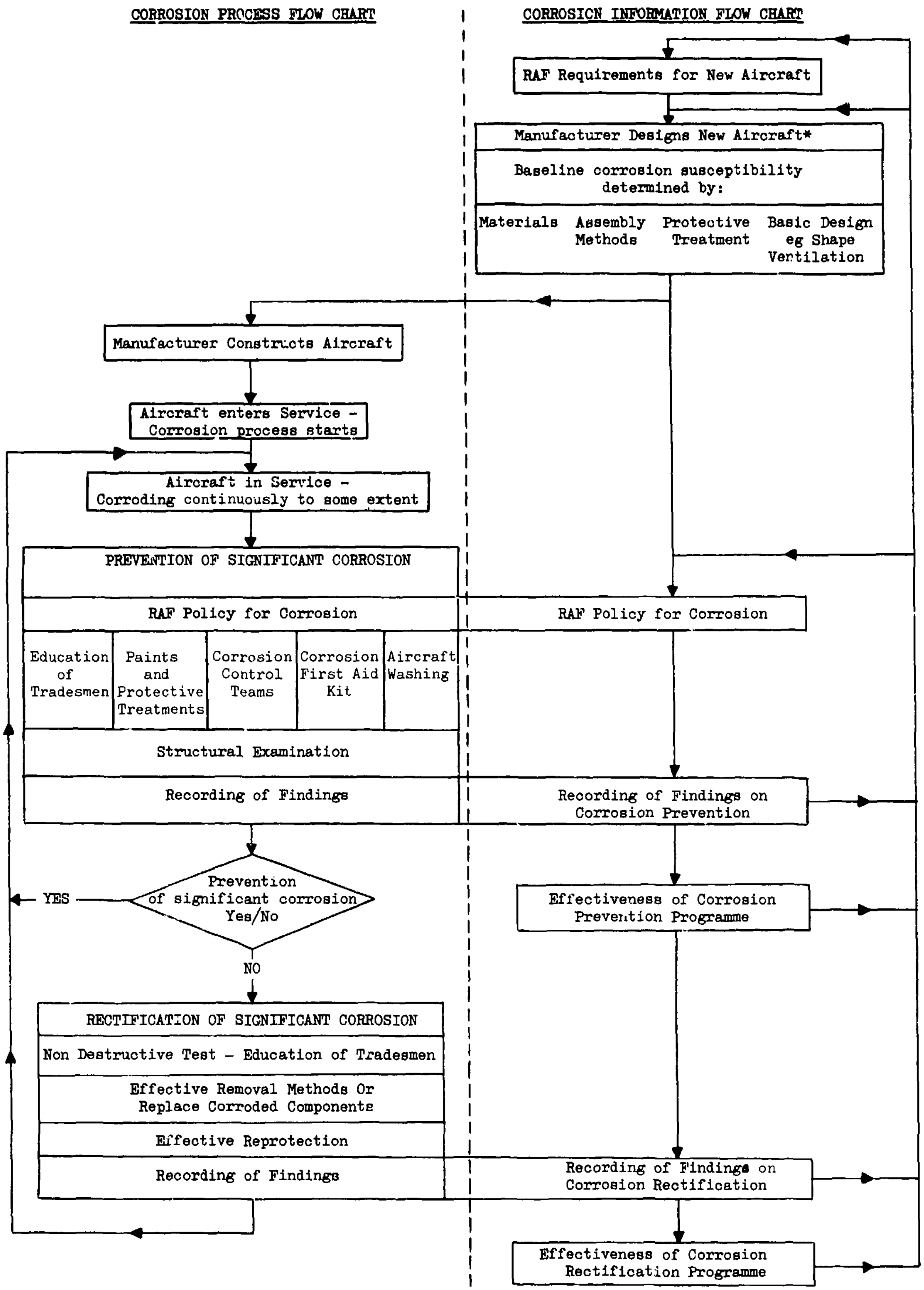
20. We are not aware of any major breakthroughs in corrosion prevention. For existing aircraft types we can only control the degree of in-service corrosion by use of better protectives. We therefore think that corrosion will continue on in-service aircraft and the most significant costs savings will be made by first slowing down the rate of corrosion, then by early detection and rectification before repairs become

extensive and costly. In other words, with the current state of the art we can only delay the inevitable. We intend our recordings of costs and the effectiveness of our programme against corrosion to shape both our future aircraft requirements at the design stage and our maintenance policy developments. We, as maintenance engineers must specify to the designer that all aircraft, and particularly those used in the maritime role are to be manufactured from materials that have a demonstrated high resistance to corrosion in the operating environment. Furthermore, they must be adequately protected on assembly. We should, therefore perhaps, look forward to the composite fibre reinforced plastic aircraft.

21. Figure 8 shows the effectiveness of our very active programme on the Nimrod. The Figure shows an increasing trend in rectification costs ever since the programme started. However, we are continuing to monitor the trend and hope that rectification costs will tail off as rectification becomes less as more corrosion is rectified out and prevented from further occurrence by our preventative measures. Nevertheless, this paper would be incomplete if it did not show the cost of corrosion in relation to the whole perspective of maintenance costs. For the RAFs most corrosion expensive aircraft, the Nimrod, our findings show that corrosion maintenance is only a small percentage of the total maintenance cost of the fleet. For other aircraft the cost will be even lower and less significant. Moreover, the RAF has never lost an aircraft because of corrosion and in the days of severe pressures on defence budgets we must be careful not to allocate more resources to the problem of corrosion than are justified.

CONCLUSIONS

22. Corrosion maintenance costs, at worst, are a small percentage of total maintenance costs. Nevertheless corrosion is a serious problem for some aircraft types because it reduces aircraft availability and consumes manhour resources. Aircraft size, age, environment and construction are the factors which determine individual corrosion maintenance costs. If we accept we have to operate aircraft in poor corrosion environments then the only variable which can be controlled is aircraft construction. This variable is controlled by the aircraft designer. We need to specify to him the need for excellent corrosion resistant materials, good corrosion resistant basic design and ample protective treatments on manufacture. In service maintenance against corrosion only compensates for poor design. All the protective measures we take only appear to delay the inevitable; there are no major breakthroughs in corrosion prevention. We believe it is cheaper to prevent corrosion than to allow it to occur and then have to undertake extensive costly repairs. In the RAF the elements of preventive maintenance are policy, education of tradesmen, corrosion control teams, paints, protective treatments, a corrosion first aid kit and aircraft washing. If prevention is unsuccessful then we either blend out corrosion by several methods or replace the defective component. We then replace the original protection scheme and in many cases use an additional supplementary protective. We record corrosion work at all stages and in the case of the Nimrod aircraft we are comparing the costs of corrosion prevention against rectification to find the effectiveness of our programme. We intend to use our findings to influence our maintenance procedures and more importantly to shape our future design requirements so that the designer produces an aircraft that does not corrode significantly during its service life.



Note: *Not necessarily to RAF requirements

Figure 1 - AIRCRAFT CORROSION IN THE ROYAL AIR FORCE

AIRCRAFT TYPE	CORROSION MAINTENANCE COST FACTOR
Small training aircraft eg Jet Provost	1
Smaller combat aircraft and modern land based helicopters eg Jaguar, Lightning Puma	5
Larger combat aircraft and modern marine environment helicopter eg Phantom and Sea King	15
Medium sized Transport aircraft and old marine environment helicopter eg Hercules and Wessex	25
Old bomber aircraft eg Vulcan	35
Large transport aircraft and maritime patrol aircraft	85

Figure 2 CORROSION COSTS BY AIRCRAFT TYPE

NIMROD SYSTEM	% OF TOTAL CORROSION RECTIFICATION COSTS
Mainplane	45
Fuselage	29
Fuel System	4
Flying Controls	4
Air Conditioning	3
Tail Unit	3
Hydraulic Power	2
Engines	2
Fire Protection	1½
Landing Gear	1
Ice/Rain Protection	1
Tactical Sensors	½
Lights	½
Auxiliary Power Units	½
	TOTAL 97%

Figure 3 RELATIVE CORROSION RECTIFICATION COSTS FOR NIMROD SYSTEMS

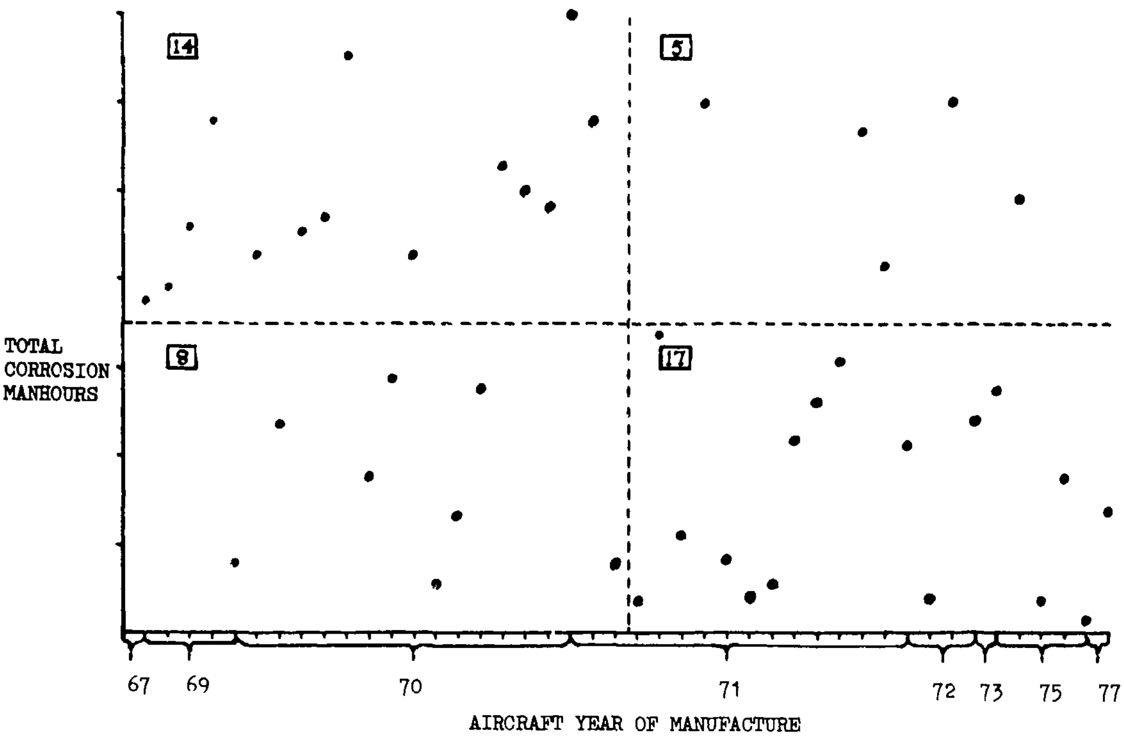


Figure 4 NIMROD CORROSION RECTIFICATION COSTS AGAINST AIRCRAFT AGE

Figure 5 CORROSION FIRST AID KIT

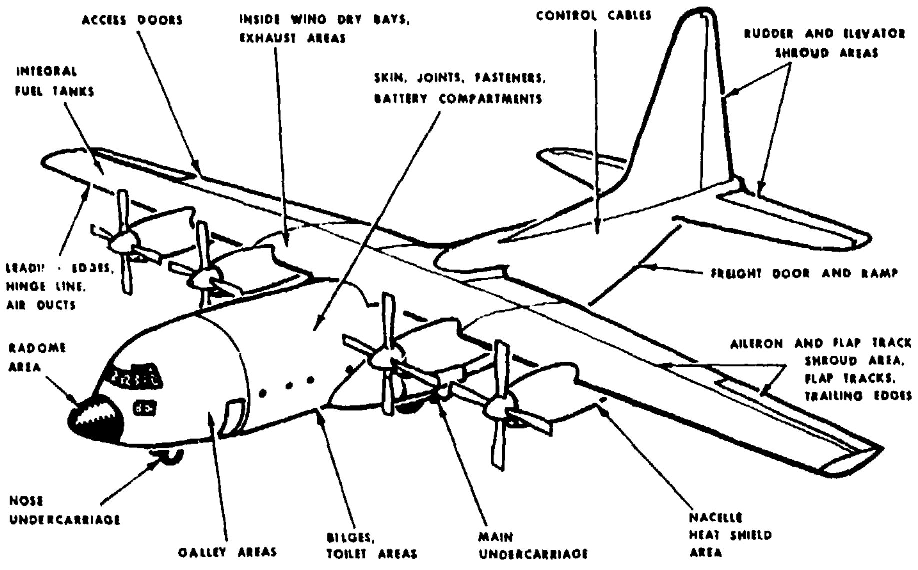


Figure 6 CORROSION PRONE AREAS ON TRANSPORT TYPE AIRCRAFT

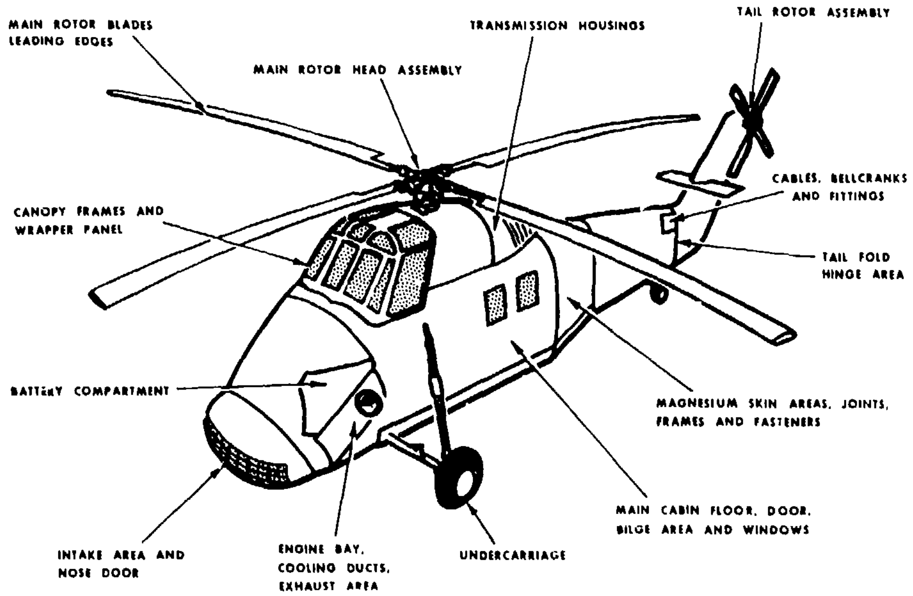


Figure 7 CORROSION PRONE AREAS ON HELICOPTER TYPE AIRCRAFT

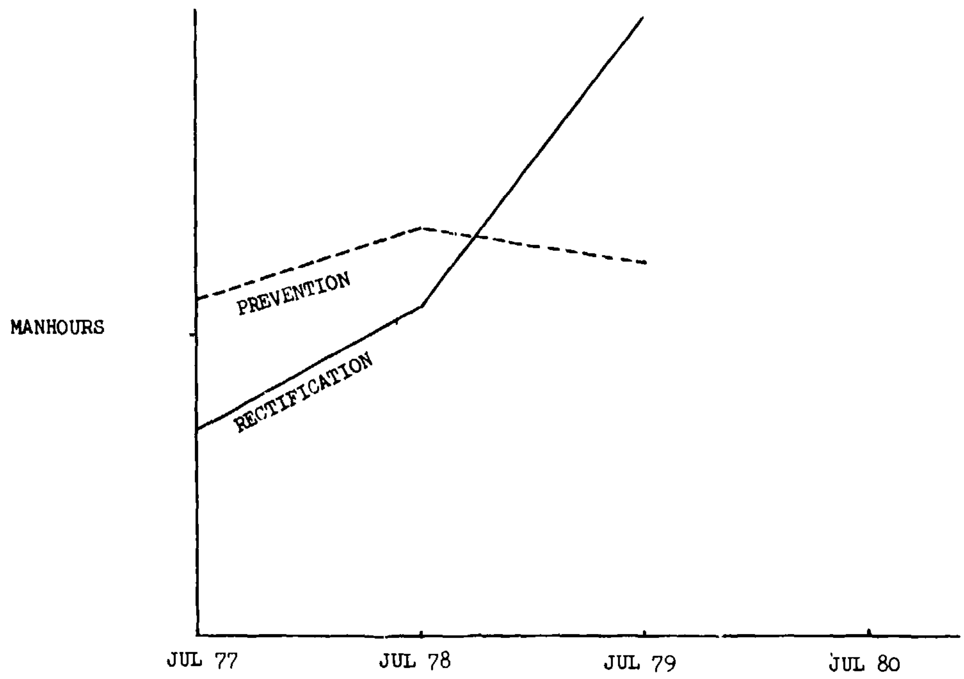


Figure 8 EFFECTIVENESS OF NIMROD PREVENTATIVE PROGRAMME

An Airline View of the Corrosion Problem

R G MITCHELL Asst. Manager
Aircraft Engineering (Structures)

British Airways
PO Box 10
Heathrow Airport (London)
Hounslow TW6 2JA
England

Summary

Although the corrosion phenomenon is well understood by aircraft manufacturers and operators alike, most current aircraft types continue to exhibit many of the fundamental corrosion defects shown by earlier designs. It is estimated that the total annual cost to IATA member airlines is around $100 million based on 1976 operations. Environmental and maintenance effects are important and should be fully understood in their importance in minimizing corrosive attack. In addition to the more common forms, filiform corrosion and microbiological contamination present hazards to aircraft operating in certain areas of the world.

Temporary water displacing fluids are becoming common in their use, and subject to certain limitations are providing valuable short term protection.

The new FAA design rules will require the effects of corrosion to be considered at the design stage which should result in an improved product for the operator. In addition the IATA document Guidance Material on "Design and Maintenance Against Corrosion of Aircraft Structures" specifies practices which should also improve the overall product.

General Introduction

The aircraft utilisation rate is laid upon a foundation of known work programmes which stipulate that individual aircraft will be undergoing maintenance for block periods of time during the year. It is apparent therefore that in order to support the Commercial Department plans, an extremely well devised maintenance programme is required. For an airline to operate at optimum efficiency, the maintenance programmes must be planned to ensure that the work requirement is matched by the necessary spares, materials, tools, equipment and labour at the right stages during the hangar visit.

The unexpected and non-scheduled problem is therefore, strictly an economic embarrassment. The discovery of a fatigue crack, corrosion or any of the other mechanical faults which must be repaired on an urgent basis are the ones which really cause the headaches.

In its simplest form the airline engineering base can be regarded as a facility for carrying out planned maintenance and changing or repairing worn out components. This view is of course unrealistic because somewhere, someone is intent on driving a ground vehicle into the side of an aeroplane thus causing a service delay which has wide repercussions in many directions. Similarly the work necessary at base to repair an unexpected crack or corrosion in a major piece of structure can soon seriously upset the best planned engineering commitment and rapidly lead to non-availability of aircraft.

Modern aircraft design makes increasing use of integrally machined panels and components which in themselves are rather more difficult to repair in terms of time and complexity than the conventional rivetted skin/stringer combination. It also follows therefore that the supply of spare parts in the event of a fleetwide problem could pose serious incorporation difficulties to the operator.

It is probably true to say that the corrosion phenomenon is well understood by both the manufacturing and airline industries, yet the annual costs of corrosion to the operators remain appallingly high. Furthermore, most aircraft types recently produced exhibit many of the same fundamental corrosion defects as those earlier models produced two decades ago. The reasons are manifold, including custom and practice unchanged over the years, higher initial costs to provide better protection during manufacture, unawareness on the part of the designer of realistic operating conditions, a gradual deterioration of the protective finishes, and an inability on the part of the operator to maintain the airframe to the "as received" condition. It is true to say that once the onset of corrosion occurs, the operator is generally fighting a losing battle, but since aircraft are now in service for much longer periods - around twenty years is typical - a general improvement in the basic protection is essential to minimise operational costs and to maintain structural integrity.

Several IATA Member Airlines have made a preliminary analysis of their corrosion costs based on the annual costs of scheduled maintenance, modification, and replacement.

The results of these analyses show the financial cost of the corrosion problem which can be expressed in several ways:-

(i) Direct cost per flying hour between $5 and $12, depending on operators and aircraft type (not including maintenance overhead).

(ii) Percentage of direct airframe maintenance costs between 6% and 8%.

(iii) Total annual direct cost for IATA Member Airlines would be close to $100 million based on 1976 operations.

It should be noted that the values represent costs for a range of operators and aircraft types. The lowest value is very conservative and is largely based on one operator's actual modification project costs only. The higher value is probably closer to the true cost since it is based upon a breakdown of actual modification, routine maintenance and inspection costs.

Closer examination of these figures reveals that the major component in the cost values associated with corrosion prevention and control is due to labour costs. An additional cost not reflected in the above figures is the unscheduled downtime both at main base and route stations.

Environmental Considerations

Environmental effects both in the air and on the ground are very important factors in the ability of a structure to withstand corrosive attack. It highlights the differences found by operators of similar aircraft types around the world and indeed should be a prime consideration together with the operational role and flying rate when the operator establishes his corrosion prevention and control programme.

In a dry climate, corrosion usually progresses very slowly, however if the same aircraft is exposed to a warm wet climate with salt water nearby, light corrosion if untreated can become very severe in a very short space of time. Similarly temperature and atmospheric changes during each flight make a contribution to corrosion attack. An aircraft may depart from an airport where the temperature and humidity is high, climb through industrially polluted air and rain, cruise at subfreezing temperatures and land where the climate is again hot and humid. During these phases of flight, moisture condenses and airborne salts accumulate on the skin, in crevices and in structural enclosed areas such as flap cavities and undercarriage bays. The structure may already be contaminated by leakage from fluid sources, exhaust gases and runway salts or other contaminants and the overall effects of these combined actions may directly attack the structure or absorb and retain contamination thereby providing an excellent environment for corrosion to develop.

The wide range of materials used during maintenance or in operating the aircraft, or indeed carried as freight comprise additional hazards to the structure in terms of causing corrosion initiation. Some of these conditions and contamination sources are listed as follows:-

Base Airport and Operational Environment

(a) Climate/humidity.
(b) Location relative to salt water.
(c) Condensates from passengers and livestock.
(d) Airborne salts and industrial impurities.
(e) Sunlight and ozone affecting rubber and plastic materials.
(f) Runway salts and contaminants.

Operational/Maintenance Materials and Hazards

(a) Oils and [illegible]ulic fluids.
(b) Cleaning materials and paint strippers.
(c) Maintenance [illegible]ions causing scratches and abrasions.
(d) Accidental [illegible]age during maintenance and in operation.
(e) Battery acid.
(f) Exhaust gases.
(g) De-icing and de-frosting fluids.
(h) Toilet and galley spillages.
(i) In flight turbulence causing spillage.
(j) Cargo breakage and/or spillage.
(k) Contaminated [illegible] (kerosene).

Most of these sources and conditions are quite well known and the list is not intended to be exhaustive. For example, foreign objects left lying around within the structure at build or during maintenance can rattle and abrade, and repair areas require thorough cleaning afterwards to remove swarf, loose fasteners and so on.

It is vitally important that all materials used in maintenance are checked out on their total effects on aircraft materials. Paint strippers which may be ideal for the immediate task can be disasterous on plastic materials (cabin windows) beside causing a possible disposal problem. Similar considerations should also be extended to chemicals which may directly or indirectly be used on or around the aircraft, such as insecticides and fire fighting materials i.e. foams and the like, used by different airport authorities around the world. It is essential that following any incident involving the use of fire extinguishing compounds on aircraft structures or furnishings, rapid steps are taken to thoroughly clean the affected areas otherwise the aircraft might be very seriously contaminated.

In the case of the carriage of dangerous materials in freight holds, the International Air Transport Association (IATA) publish a handbook "Restricted Articles Regulations" which the shipper must declare and observe when offering such materials for transportation to the operator. However cases have occurred where highly corrosive materials have contaminated structures due to incorrect declarations. For example a shipment labelled scientific instruments may consist of instruments containing mercury which if damaged can cause severe contamination problems to the operator.

Causes of Corrosion

When paint has deteriorated or plating and protective finishes are damaged, the base material is vulnerable to corrosive attack. Most common forms of corrosion are electrolytic in nature and once corrosion starts and affects the internal structure of the metal it can continue even though the surface is subsequently protected. On many occasions, areas which have been blended or mechanically worked have exhibited subsequent signs of corrosion due to the initial corrosion not being completely removed. It is an unfortunate fact that aircraft materials which require a high strength/density ratio are generally all susceptible to corrosion attack. In general the higher the strength the higher the susceptibility to attack.

Brief Review of Common Forms of Corrosion

1. Surface Corrosion
   Etching or pitting of metal surfaces caused by reaction between metal and moisture containing contaminants. Accelerated by conditions of high humidity and temperature.

2. Dissimilar Metals
   Coupled in the presence of a suitable electrolyte process may be similar to a simple acid battery.

3. Intergranular Corrosion
   Seriously affects metal strength and is caused by breakdown of grain structure at the grain boundaries due to corrosive attack. Condition is difficult to detect in the early stages. As corrosion progresses, lifting of metal surface occurs. Exfoliation is one form of intergranular corrosion. Some materials are very prone to attack where machining occurs across the grain of the material.

4. Stress Corrosion
   Occurs in some alloys which are susceptible to cracking when under sustained tensile stress and are exposed to corrosive environment. Small intergranular cracks occur at the bottom of corrosion pits and the tensile stress causes cracks to open exposing fresh metal to corrosive attack. Failure occurs due to combined effects of stress and corrosion. It is important that machining or fitting practices during assemblies avoid inducing stress into a component. It is good practice to avoid using loose gap fillers on assemblies requiring fairly frequent dismantling. Mating dimensions should be designed to avoid the use of shims or loose parts which sooner or later will be lost.

5. Fretting Corrosion
   Occurs where mating surfaces have slight relative movement. No corrosive agent is necessary for fretting to occur.

6. Bonded Structure Delamination
   Often occurs due to corrosion where moisture enters and attacks the bond or internal structure.

Specific Forms of Corrosion

A number of specialised forms of corrosion have occurred mainly in areas of high humidity and temperatures. These are:-

1. Filiform Corrosion
   This is a tunneling thread like corrosion which develops under paint schemes usually adjacent to fastener heads. Corrosion begins as a superficial attack of the aluminium clad surface which unless treated can lead to skin exfoliation or fastener corrosion. The early signs are paint blistering or loss of paint adhesion, and corrosion results from galvanic action between areas of different electrochemical potential on the aluminium skin surface. Moisture which has penetrated the paint film acts as the electrolyte.

2. Integral Fuel Tank Corrosion
   Micro organisms which live and breed in water contained in jet fuel can cause serious corrosion of metal surfaces in integral fuel tanks. The micro organisms form dark coloured slimy sludge in the fuel tanks and can deteriorate fuel tank sealant, protective treatments and corrode tank pipes and wing structure. It can clog strainers and fuel filters and eventually cause fuel tank leakage and structural failure. Fuel tank sumps must be drained frequently to check for, and reduce the water content in the fuel. Fuel additives can be used to kill the micro organisms. This particular problem seems to be most prevalent to aircraft operating or standing for long periods of time in tropical conditions.

   The most recent information on this subject would indicate that zinc rich epoxy paint schemes provide the best internal fuel tank protection, and one manufacturer has used strontium chromate in tablet form located inside plastic containers permanently attached to the internal wing structure to combat the problem. British Airways have experienced this form of contamination to some degree and we add Biobor to the fuel as found necessary. Aircraft that are inactive for lengthy periods are also treated with Biobor prior to storage.

Corrosion Problem Areas

Experience shows that the following areas in aircraft are particularly prone to corrosive attack.

1. Galley Locations
   Liquid spillages are the prime cause, coffee, fruit juices and other liquids are particularly severe on light alloy structure and despite the very best sealing efforts that are made in these areas, the problem has not been completely eliminated. It would also seem that galleys are usually positioned at each end of the aircraft invariably over structure which is difficult to inspect from underneath and occasionally adjacent to pressure bulkheads and electronic equipment.

2. Toilets and Washing Areas
   The usual corrosion source is urine contamination and water spillage therefore very special sealing efforts are made to minimize the corrosion hazard. Since both galley and toilet areas are particularly prone to corrosion, the inspections in these locations are particularly intensive.

2. Toilets and Washing Areas Contd.
Spillage can also occur during in-flight turbulence which invariably seems to occur whenever the cabin staff are serving meals!

3. Freight Holds
Freight areas and the structure beneath the holds suffer corrosive attack resulting largely from spillage or breakages from cargo. The structure beneath the hold is usually at the bottom of the aircraft and collects moisture which drains into these lower areas. There are very strict packaging requirements for certain restricted cargo particularly corrosive liquids which shippers must observe before a consignment can be carried. Passengers also carry strange items in their personal baggage and it has been known for a lead acid battery to be packed into a suitcase. The resulting damage to this, and the surrounding baggage was to say the least - considerable. Some baggage handling facilities are not exactly careful in transporting and stowing baggage and again breakages can occur.

The normal treatment in cases of spillage is to locally clean the area at the time the spillage is discovered and then to thoroughly inspect the aircraft when it returns to base.

4. Condensation
Condensation from passengers and livestock is another potential source of corrosion. Soundproofing which is adjacent to the fuselage skin absorbs moisture and can literally lay like a wet blanket against the structure. On one aircraft type it was found that the empty weight had increased by approximately 400 kgs. due to this cause.

Temporary Protection Schemes

Most operators now make use of water displacing fluids as a temporary protection under adverse conditions. British Airways have used the materials both internally within fuselage and wing areas, and externally around undercarriage components and the experience to date has been good. Areas susceptible to corrosion have been successfully treated by repeat applications of the fluid and the corrosion rectification previously necessary has been significantly reduced. It is difficult to estimate the life expectancy of the treatment since this obviously depends on the environment, but six months in an exposed undercarriage area to two years within a fuselage would be typical repeat application frequencies.

The fluid treatment is most beneficial when the basic paint protection scheme is in good condition since it will displace water from tiny crevices and similar areas prone to corrosive attack. Indeed one manufacturer treats the lower fuselage areas after assembly as an added protection to the paint schemes before delivering the aircraft to the customer.

We have over the years attempted to locally repaint and touch up internal structure particularly in dirty areas such as the lower fusealge, but it is well nigh impossible to clean the structure around stringers, brackets, rivets etc. to the high degree of cleanliness required for re-painting and it is felt that water displacing fluid is probably a more effective overall treatment.

It should be emphasised of course that these fluids provide temporary protection only and in no way should be considered to replace a good sound permanent protection scheme during initial construction of the aircraft.

There is a fear in some quarters that the widespread use of these fluids will have an adverse effect on fatigue lives of joints and indeed British Airways collaborated with The Royal Aircraft Establishment at Farnborough to conduct constant amplitude faituge tests on representative fuselage lap joint specimens. It was found that on bare assembled joints i.e. with no protective coating between the plates, the reduction in frictional effects caused by the fluid did cause a significant reduction in fatigue life. Other sources state that above plate thicknesses of about 1.5 to 2.0 mm (.063"- .071") the fatigue effect is minimal.

Design Requirements and IATA Guidance Material

The design requirements for new aircraft in the transport category have recently changed (FAR 25.571, JAR 25). The manufacturer is now charged with assessing the effects of corrosion and accidental damage in addition to fatigue on the damage tolerence of the structure during the declared life of the airframe at the design stage. Recent events have produced the Structural Audit or Supplemental Inspections for existing aircraft but under the new design rules, these additional requirements must be considered at the outset. These changes should result in an improvement in airframe protection as far as the operator is concerned. During the late 1970's a team of airline representatives, including myself for British Airways met at the IATA offices in Montreal to discuss the corrosion problem. This resulted in the publication of IATA document "Guidance Material on Design and Maintenance Against Corrosion of Aircraft Structures". (Doc. Gen/2637)

This document is a comprehensive review of corrosion as seen by the airlines. It covers the basic problem and specifies methods by which manufacturers can meet the objectives. The document has largely been accepted by the major aircraft constructors and compliance with the majority of the important recommendations has resulted. Most of the good practices to be specified here are spelt out in great detail in the document and should be considered as supplementary to this paper.

Inspection Methods

The majority of inspections are performed visually where the experienced eye can readily assess the overall condition and detect specific defects such as surface flaws, local deformation, slight bulges on skin or colour variations which might be indicative say of corrosion or leaks. The trained and experienced eye forms the vital part of the inspection process since it is linked to the best computer available in the field, the human brain, where judgement, experience and memory plays such an important part in the overall assessment and interpretation of structural condition. The inspector is aided by well established optical magnification devices including remote viewing light probes. Various dye penetrant methods are available and of course the whole field of NDT which is constantly improving and increasing its capability. Indeed once a defect position is identified an appropirate NDT procedure is capable of finding very small crack or defect indications. We all tend to make increased use of the sophisticated NDT techniques available nowadays. Low frequency eddy current equipment which is capable of penetrating one material thickness to search for defects in another layer or inside the bore of a fastner hole is now invaluable. It should be emphasised however that NDT inspections are generally very specific with the technique being developed to search for a given defect at a given location.

The eyeball inspection still constitutes the major inspection activity in maintaining structural integrity.

Inspection Opportunities

The Maintenance Checks on British Airways aircraft are as follows:-

(a) Transit Checks

The most frequent inspection takes place at the transit check prior to each flight.

Comprising - Prior to Departure Checks, Route Station Transit, London Turnround Checks, Terminating Station Checks. These inspections from ground level provide the opportunity to detect fairly gross forms of damage resulting from natural causes and from accidental damage, i.e. catering trucks and ground equipment collisions with aircraft. In all cases however, whenever and wherever a significant structural defect is found or damage is inflicted, it is a requirement that stations report such events to base, where if necessary, appropriate repair advice can be given prior to further flight.

It is considered that gross damage over the lower fuselage up to, say, cabin window level, around entry door apertures, together with the lower surfaces of the wing and tailplane can usually be readily detected on this type of check. It is very difficult to define gross damage since the inspection, of course, takes place in the open air and in the prevailing weather and lighting conditions, however torches are used in darkness to supplement the airport ramp lighting.

Fuel leaks have been detected on these checks, which in several cases were indicative of fatigue damage.

This check would also be used to inspect the aircraft for signs of damage following reports of inflight turbulence, lightning or bird strikes, or following a heavy landing. Fuselage creases and engine nodding has been detected following heavy landings.

(b) Service Checks

Typical frequencies:	700/800 flying hours VC10 and B707
	800 flying hours L1011
	1350 flying hours B747

This inspection is a general visual examination of the complete exterior of the aircraft with flaps extended supplemented by opportunity inspections of such areas where access is required for maintenance and servicing. It is a hangar inspection in good lighting conditions with some access equipment around the aircraft such that upper parts of the external surface can be examined from a distance considered adequate to detect fairly gross forms of damage, i.e. deformation, distortion, long standing nicotine staining and obvious cracks. The term SCAN inspection is applied to this external inspection. The check is also used to monitor or inspect any items on special surveillance, as we try not to impose any specific inspections at frequencies less than the Service Check unless considered essential for an urgent structural integrity check.

(c) Intermediate Check

Typical frequencies:	1500 flying hours B707-400
	2000 flying hours B707-300
	3000 flying hours L1011
	4000 flying hours B747

This inspection requires a close detailed visual examination of the external structure where quite small defects, say cracks up to 1" long, or early signs of corrosion should be readily detected by visual means. In addition some NDT inspections are required for specific areas, and internal zonal type inspections also take place of the more critical areas. Whenever a panel is removed to attend to the needs of a component or system, an inspection of the structure is also required prior to re-fitting the panel.

The aircraft is fully jacked in the hangar with full access staging around the aircraft. Wherever possible any minor or temporary structural repairs are carried forward by repeat inspections, at the lower checks for assessment for permanent repair during this check.

(d) Inter-Supplemental Check

Frequency:	6000 flying hours or 2 years B707-400 or VC10
	8000 flying hours or 2 years B707-300
	6000 flying hours TriStar
	8000 flying hours B747

(d) Inter-Supplemental Check Contd.

In addition to the Intermediate Inspection requirements this check requires a more detailed visual and NDT inspections of selected internal structure and examines particularly the lower fuselage including pressure bulkheads and internal door surround structure. Some Structure Sampling Inspections are also carried out during this check.

Major Check

Frequency:	10000 flying hours or 3 years	B707-400
	16000 flying hours or 4 years	B707-300
	12000 flying hours or 3½ years	SVC10
	16000 flying hours	TriStar
	24000 flying hours	B747

In addition to the previous inspection requirements, this is the check during which most of the deep internal structural inspections and sampling inspections occur, both by visual and NDT methods.

Reaction to Inspection Findings

Figure 1 shows the prime sources of information received internally and externally by British Airways and the normal action channels used for resulting inspections and/or implementing corrective actions.

Formal documentation, such as Service Bulletins and Directives and the like are received within our Technical Services Department and documentation is sent to the appropriate Engineering Group for review and recording of the action taken. In this way we ensure that each and every document is properly accounted for and does not become mislaid or failed to be acted upon (unless a justifying statement is made that action is not required or has been covered by alternate action).

The normal response following the discovery or notification of a significant defect is by the Special Check route. This is normally a once-off inspection carried out across the fleet, the timing and applicability of which depends on the nature and severity of the defect. The aim being to inspect first those aircraft with similar or greater flying hours/cycles to the aircraft containing the defect. Figure 2 details the Special Check requirements and special Maintenance Work Requirements resulting from our own findings, Service Bulletins, Advisory Reports and the like, issued by Structures Group alone over the periods shown. The tabulation shows that we have called for a considerable number of additional inspections over and above those carried out by the routine inspections specified in our own Maintenance Schedule. In order to set these numbers in perspective, those inspections which were related to significant structural problems, including those defects associated with cracking and corrosion have been indicated separately under some headings. The others being more related to operational problems such as wear checks, high door operating loads, removing batches of suspect tyres and so on.

Depending upon the findings of the Special Check, a change may be introduced to the Maintenance Schedule or a modification called up etc.

REACTION TO INSPECTION FINDINGS AND EXTERNALLY RECEIVED INFORMATION/REQUIREMENTS

MAIN SOURCES OF INFORMATION

BA INSPECTION FINDINGS	(Routine inspections (Structural sampling inspections (Developing trends from work cards/general experience
MANUFACTURERS	(Service Bulletin (Service cable (Service News Letter (In Service Activities Report (Structural Advisory Note
REGULATORY AUTHORITY	(Mandatory Requirement (Airworthiness Directive - AD) (CAA List of Additional Directives, Mandatory Occurrence (Reports & Feedback (Similar infomation from USA)
OTHER OPERATORS	(Reports
ENGINEERING ACTION	(Special Check (Inspection for Condition) (Maintenance Work Requirement (BA Modification (BA Repair Scheme (Design Deviation Authorization (Approved Maintenance Schedule (Maintenance Manual Revision (Technical News Sheet

FIG. 1

SPECIAL CHECKS & MAINTENANCE WORK REQUIREMENTS ISSUED BY STRUCTURES GROUP

Aircraft Type and Year	ATA 32 U/C Wheels Brakes & Tyres	52 Doors	53 Fuselage	54 Nacelles	55 Vertical and Horiz. Tail	56 Windows	57 Wings Incl. Flaps & Ailerons	GENERAL Incl. Emerg. Equip. In-Flt. Turb. Checks	TOTAL
B707 1969	9	2	4	3	5	0	11 (3)	1	35
1970	13	10	5	1	2	1	4 (1)	2	38
1971	3	5	8	1	5	1	15 (2)	1	39
1972	9	0	8	2	3	0	14 (2)	2	38
1973	11	5	5	0	2	0	14 (3)	0	37
1974	11	3	6	1	0	1	14 (5)	0	36
1975	10	0	4	1	0	1	20 (6)	1	37
1976	14	5	8	3	2	2	10 (4)	2	46
1977	4	3	6	3	2	1	16 (11)	4	39
1978	5 (3)	0	3	1	4	1	7 (4)	5	26
1979	5 (2)	4	0	1	2	0	6 (5)	1	19
	94	37	57	17	27	8	131	19	390
VC10 1969	3	1	4 (0)	2	4	0	3	0	17
1970	5	2	5 (2)	0	1	1	0	0	14
1971	11	2	4 (2)	0	6	0	2	0	25
1972	3	0	1 (1)	0	1	0	0	0	5
1973	2	0	2 (1)	0	0	0	0	0	4
1974	6	4	8 (3)	1	1	1	2	2	25
1975	5	0	5 (2)	1	0	0	4	1	16
1976	7	6	3 (1)	1	3	0	5	6	31
1977	3	7	4 (2)	4 *	0	0	1	6	25
1978	1	4	3 (2)	3 *	1	1	2	2	17
1979	4 (2)	1	5 (0)	2	1	0	1	1	15
	50	27	44	14	18	3	20	18	194
B747 1974	12	23 (6)	3	3	0	0	16 (2)	1	58
1975	15	12 (2)	4	1	0	0	21 (4)	2	55
1976	16	17 (3)	3	0	1	2	13 (3)	9	61
1977	14 (3)	6 (2)	5 (5)	0	0	3	3 (2)	13	44
1978	9 (1)	8 (2)	7 (3)	2	3	0	5 (3)	9	43
1979	6 (2)	5 (1)	5 (3)	7 (4)	0	0	4 (4)	2	29
	72	71	27	13	4	5	62	36	290

◯ DENOTES CRACKS & CORROSION

* INCLUDES VIBRATION STUDY

FIG. 2

Fig.3 Illustration shows a badly corroded seat track located beneath a galley unit. Corrosion has occurred where a steel galley attachment fitting was located in the light alloy seat track in the presence of liquids. The galley load restraint capability has been severely degraded

Fig.4 Photograph shows the excellent paint removing qualities of certain products carried as Air Freight! Portion of structure shown was located beneath a freight hold floor and liquid spillage caused the problem

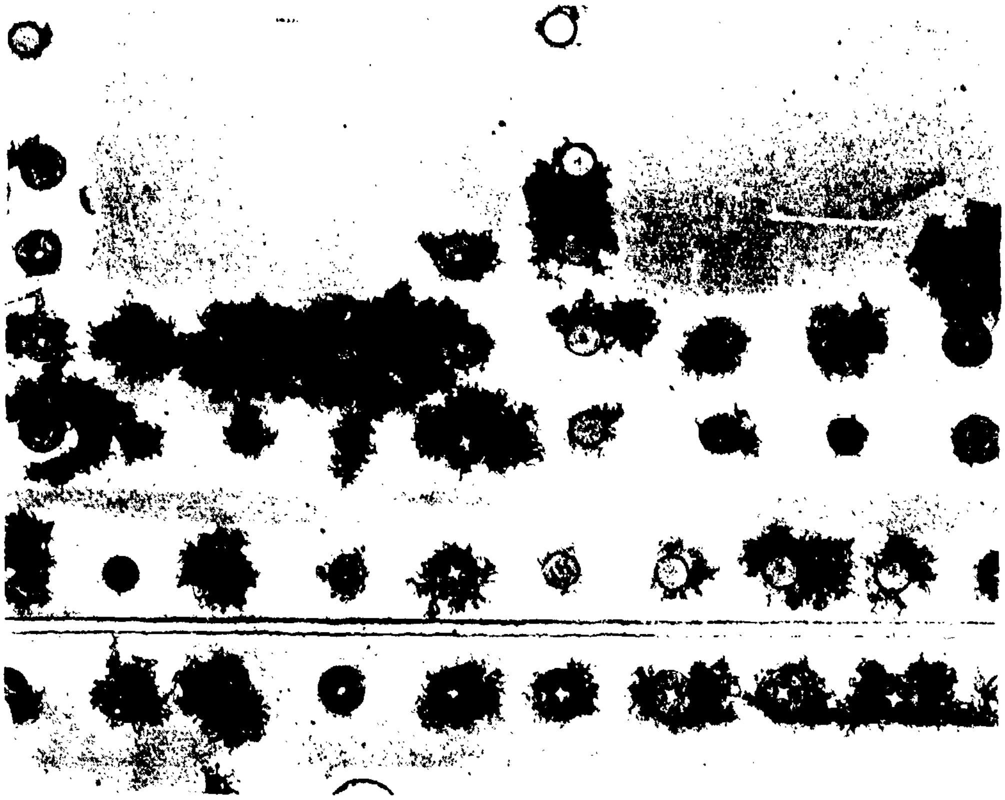


Fig.5 Illustration of filiform corrosion around steel fastener heads in light alloy (7000 series) upper wing surface

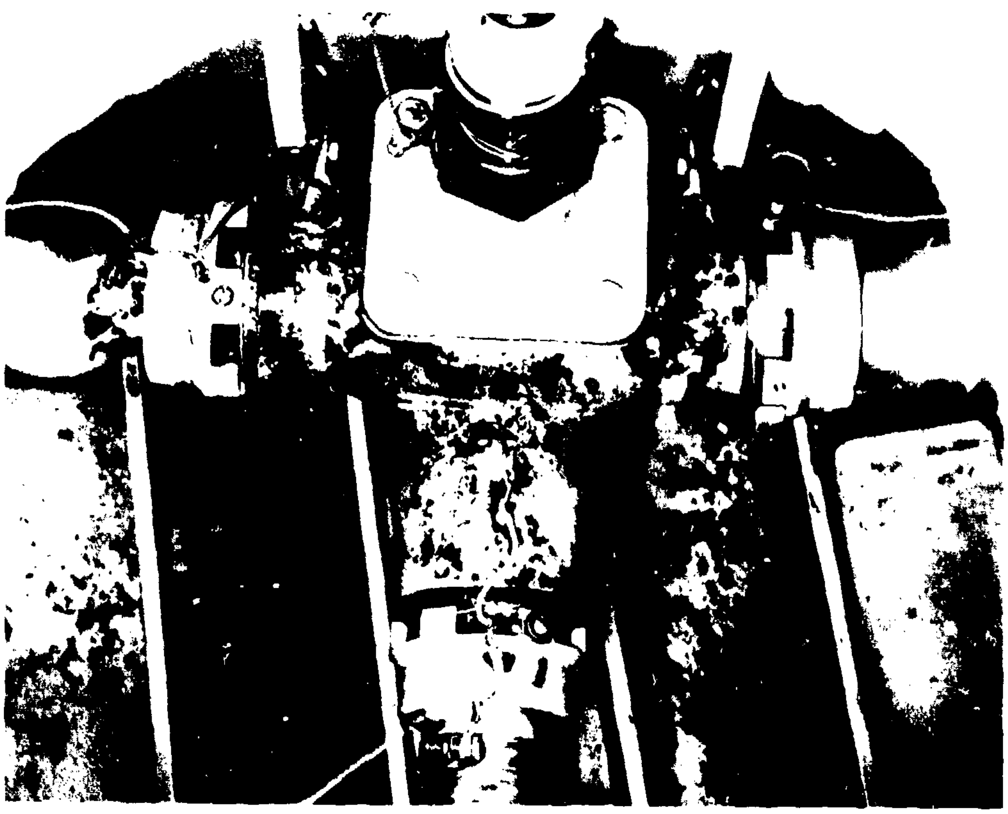


Fig.6 Illustration of contaminated jet fuel. Black coloured areas show the micro organism growth (in this case Cladosporium Resinae) which is best detected through a small quantity of fuel in the tank

Fig.7 Photograph shows a light alloy fuel pipe component which has been corroded by micro organism attack. This is apparent on the parallel portions and as overhaul surface pitting

Fig.8 However severe the Airline environment might be, this picture shows natures full hostility to mans best efforts at aircraft corrosion prevention! The photograph was taken on the flight deck of an aircraft carrier and I am grateful to the Royal Navy for providing the illustration

SOME OBSERVATIONS ON THE CORROSION OF AIRCRAFT AT THE AIR FORCE BASE IN BANDIRMA, TURKEY

M. Doruk
Middle East Technical University, Ankara, Turkey.

SUMMARY

The aim of this work is to study the types and the causes of corrosion which have been observed primarily on aircraft of Type F-5A at the Air Force Base in Bandırma, Turkey. Visual inspection showed many locations of concentration of corrosion. The vertical stabilizer attach angle (Alloy 7075-T6) fails through exfoliation corrosion and galvanic attack in the bolt holes. Galvanic corrosion has also been observed around the jaw bolts under the main wings. Another case of exfoliation attack has been found on the uplock support rib (Alloy 7075-T6 or 7079-T6) in the main landing gear well. Damage in the honeycomb assembly which appears as a debonding between the honeycomb structure and the top plate has been regarded to be a serious problem. Corrosion damage is attributed to the high corrosiveness of the atmosphere of Air Force Base laden with sea salt and polluted from industries in the neighborhood.

INTRODUCTION

In Turkey, aircraft corrosion was reported in 1972 in connection with fighters of Type F-5A at the Air Force Base in Bandırma. A general evaluation in 1976, however, showed, that the aircraft corrosion has not been restricted to a certain type of aircraft based at a specific location of the country. Instead, in addition to Bandırma aircraft based in rural areas were also found to corrode. Examples of these are Balıkesir and Merzifon. A classification of aircraft corrosion observed in Turkey according to the types and location of corrosion is given in Table 1. In general, the damage of the honeycomb assembly is the one the aircraft users find most serious. Parts, which are heavily damaged through an exfoliation type of corrosion like the vertical stabilizer attach angle have to be replaced. The same is true for parts damaged by galvanic corrosion confined to holes through which the bolts are placed.

Table 1. Classification of corrosion damage according to the type of aircraft

Aircraft	Type and location of damage
F-5A	EXFOLIATION AND STRESS CORROSION CRACKING - Vertical stabilizer attach angle (7075-T6) - Main landing gear uplock support rib (7075-T6) - Vertical stabilizer along the edge of radome - Inside of the air inlet ducts GALVANIC CORROSION - Holes in the vertical stabilizer attach angle - Holes under the wings through which the jaw bolts are placed - Holes in the magnesium alloy covering plates under the fuselage HONEYCOMB ASSEMBLY DAMAGE - Leading edge sections of wings
F-104G-S	EXFOLIATION - Inside of the air inlet ducts GALVANIC CORROSION - Bolt holes through which the vertical stabilizer is connected to the fuselage - Holes under the wings through which the jaw bolts are placed. HONEYCOMB ASSEMBLY DAMAGE - Leading edge sections of wings
F-38A, B	- Similar to the F-5A except that corrosion is concentrated on the vertical stabilizer attach part.
F-100F, D, C	- Galvanic corrosion - Wear on alclad surfaces
F-4E	- Pitting on titanium top plate of honeycomb assembly

In this paper attention will be devoted to corrosion of aircraft at the Air Force Base in Bandırma. Here, two fleets each consisting of 18 aircraft have been based since 1966. The map in Fig.1 shows the location of Bandırma as well as that of Balıkesir and Merzifon. The same map also shows the layout of the Air Force Base and the neighboring manufacturing plants. The plants worth mentioning are the Fertilizer Factory, the Sulphuric Acid Factory and the Boric Acid Factory. Other industries in the neighborhood of the Base may have an insignificant polluting effect on the atmosphere. As shown on the map, the direction of the major winds is from the northeast.

CORROSIVENESS OF THE ATMOSPHERE

Approaching the seacoast, the atmosphere is expected to be laden with an increasing amount of sea salt. The industries in the neighborhood of the Air Force Base are also expected to pollute the air with appreciable amounts of SO_2, SO_3, H_2SO_4 in form of mist B_2O_3 and other acid gases. Accordingly, the air of the Air Force Base in Bandırma must have the main characteristics both of a marine and an industrial atmosphere.

The probes of air, that were taken from three distinct locations on the Base were analysed to determine the corrosiveness of the atmosphere. The results of these analyses are summarized in the following table. In addition, the neutron-activation analysis of dust showed the presence of a number of elements. The elements that are worth mentioning are Br, I, Na, K and Mn.

Table 2. Results of Analyses of the Atmosphere

LOCATION	DUST CONTENT mg / m^3	ACIDITY ml 0,02N HCl/m^3	CHLORIDE CONTENT mg / m^3
Fleet No: 161	0.015	60	
Fleet No: 162	0.070	-	$2,8.10^{-4}$
Tower	0.017	40	

According to these results, the dust content of the air in Bandırma is comparable with that in the most densely settled locations in Ankara. The acidity, however, is 20 to 30 times higher. The chloride content is about twice the one which is characteristic of a rural atmosphere. The direction of the major winds appears to be an important factor that increases the content of pollutants in the air originating both from the sea and the neighboring industries.

OBSERVATIONS ON THE LOCATIONS AND THE TYPES OF CORROSION

There are many locations on the aircraft on which corrosion of various types has been observed. Figs.2 to 4 show the points which have generally been subject to corrosion. Basically, three types of damage have been identified at different locations of the aircraft: (1) Galvanic corrosion, (2) Exfoliation and stress corrosion cracking and (3) Damage of honeycomb assembly.

Galvanic Corrosion

1- The vertical stabilizer at the tail section of the aircraft has been a location of frequently observed galvanic corrosion. Corrosion was detected between the screws which hold the vertical stabilizer and the holes in the vertical stabilizer attach angle through which the screws are placed. Corrosion damage in these places can be attributed to a galvani type of corrosion. The crevices between holes and screws become wet and retain moisture because the rain cannot effectively wash these locations. The tendency for corrosion results from the nobler potential of screws as compared to the potential of material (7075-T6) of the vertical stabilizer. This is evident from the enlargement of the holes through which the screws are placed.

2- Cadmium coated steel jaw bolts under the main wings have been found to cause galvanic corrosion which results in damage of holes in alüminum alloy parts. Galvanic corrosion has been observed to start after removal of the cadmium coating. Smilar type of corrosion has been detected around all kind of bolts under the fuselage and wings.

Exfoliation and Stress Corrosion Cracking

1- One place of concentration of this type of damage has been the portion at which the tailwing is connected to the fuselage. Corrosion is detected on the vertical stabilizer attach angle for connection. Corrosion damage in these places is identified as a form of exfoliation or stress corrosion cracking extendig over a region of few inches. Antoher type of damage has the form of delamination. Fig.5 shows the portions of the vertical stabilizer attach angle damaged through the types of corrosion described.

2- Another case of exfoliation attack or stress corrosion cracking has been found on the uplock support rib in the main landing gear well.

Damage in Honeycomb Assembly

This type of damage has appeared as a debonding between the honeycomb structure and top plate (an Alclad alloy 7075-T6) (Fig.6). The users of the aircraft regard this damage as a serious one, because it results in the tearing of a portion of the top plate (Fig.7). The damage starts through an opening in the edges. Debonding between the honeycomb structure and the top plate is attributed to a degradation of the adhesive under the effect of the atmosphere. It is not certain whether the corrosive attack of the honeycomb structure or the top plate has an effect on the debonding process.

EXFOLIATION CORROSION OF ALUMINUM ALLOYS

Like stress corrosion, the susceptibility to exfoliation corrosion of heat-treatable aluminum alloys arises from metallurgical differences resulting from inhomogeneities in heat treatment and fabrication conditions. The heat-treatments that are applied conventionally to these alloys consist of a solution treatment followed by either natural aging at room temperature (T4) or artificial aging at elevated temperatures to optimize the tensile properties (T6). Susceptibility to exfoliation corrosion in Al-Cu-Mg alloys is maximum in the slightly underaged condition. It can, however, be eliminated by slight overaging of the artificially aged alloys.

Grain shape is also important in relation to exfoliation corrosion. The aluminum alloys in the extruded form show an elongated grain structure parallel to the surface. When alloys are susceptible to intercrystalline corrosion, the penetration through grain boundaries occurs primarily parallel to the surface. Exfoliation corrosion develops when a pressure of sufficient magnitude has been created by the insoluble corrosion products to force the grains apart. The susceptibility to exfoliation corrosion of high-strength Al-Zn-Mg alloys shows generally a smilar dependence on grain structure, but this does not appear to be true for medium-strength Al-Zn-Mg alloys.

Like exfoliation corrosion, the susceptibility to stress corrosion cracking of alüminum alloys depends on grain structure. Susceptibility of any of the wrought alloys is maximum when stressed in the short transverse direction, because the cracks tend to propagate along the grain boundaries and the area of grain surfaces normal to acting tensile stress is greatest in this orientation. Forces acting on the vertical stabilizer create tensile stresses in the short transverse direction in the attach angle which is an extruded product. Accordingly, it can be concluded that the damage of the vertical stabilizer attach angle can be attributed to a combined action of exfoliation and stress corrosion cracking. This explanation would also be valid with respect to the damage observed in the uplock support rib in the main landing gear well, since the elongated grains occur also in forgings of alüminum alloys. The exfoliation corrosion observed elsewhere (the internal surface of the air inlet ducts is an example) can also be explained by the parallelity of grain surfaces to the external surface of cold rolled sheets.

CORROSION MAINTANENCE OF AIRCRAFT

The Türkish Air Force has two principal centers for the regular maintenance of army aircraft. These centers are located at the Eskişehir and Kayseri Air Force Bases. The maintenance center at Eskişehir deals mainly with jet aircraft. Corrosion maintenance carried out to aircraft at this center every three or four years consist of the following steps:

1- Removal of old paint,
2- Washing with detergent to remove all the remains of paint,
3- Location of places where corrosion has been effective,
4- Cleaning of rusty surfaces by means of rubber bonded abrasive wheels, whereby care is exercized to remain within the dimensional limits. Otherwise the part is replaced,
5- Application of chromate conversion coating to the cleaned surfaces,
6- Replacement of heavily damaged parts like the vertical stabilizer attach angle,
7- Isolation of bolts with a special paste to avoid galvanic corrosion,
8- Application of prime coat (1 layer) and paint (2 layer),
9- Application of the camouflage paint.

ACKNOWLEDGEMENT

Acknowledgement is due to several persons who provided information and helped to clarify some of the questions, in particular to Major Köksal Matsu of the Air Force Base in Bandırma and to Captain Ayhan Tüfekçioğlu of the Türkish Air Force Aircraft Maintenance and Supply Center at Eskişehir. The outhor is indebted to N. Saygılı and D. Kut of the Ankara Nuclear Research and Training Center for analyses of the atmosphere.

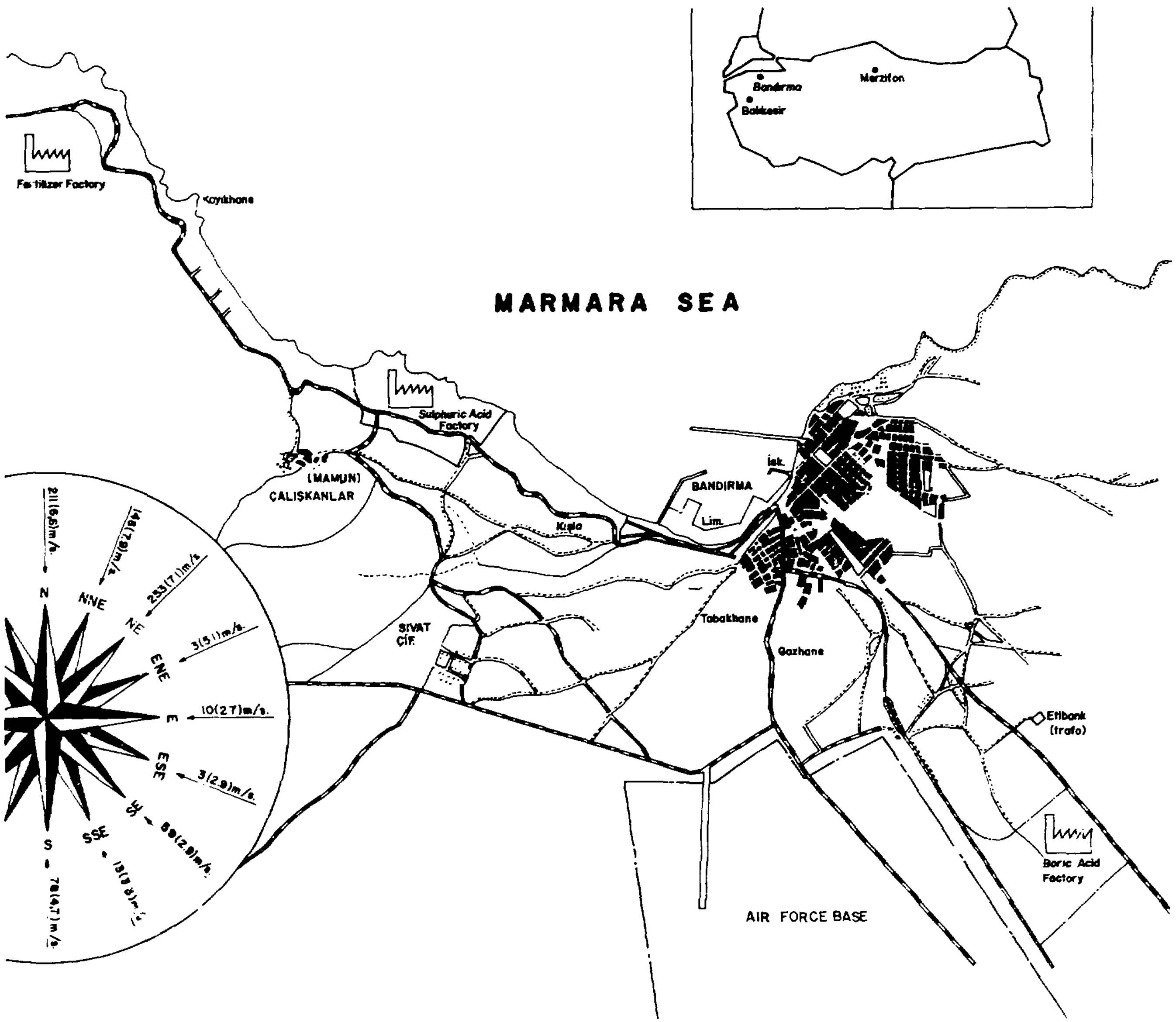


Fig.1 Layout of the Air Force Base and the neighboring industries in Bandirma

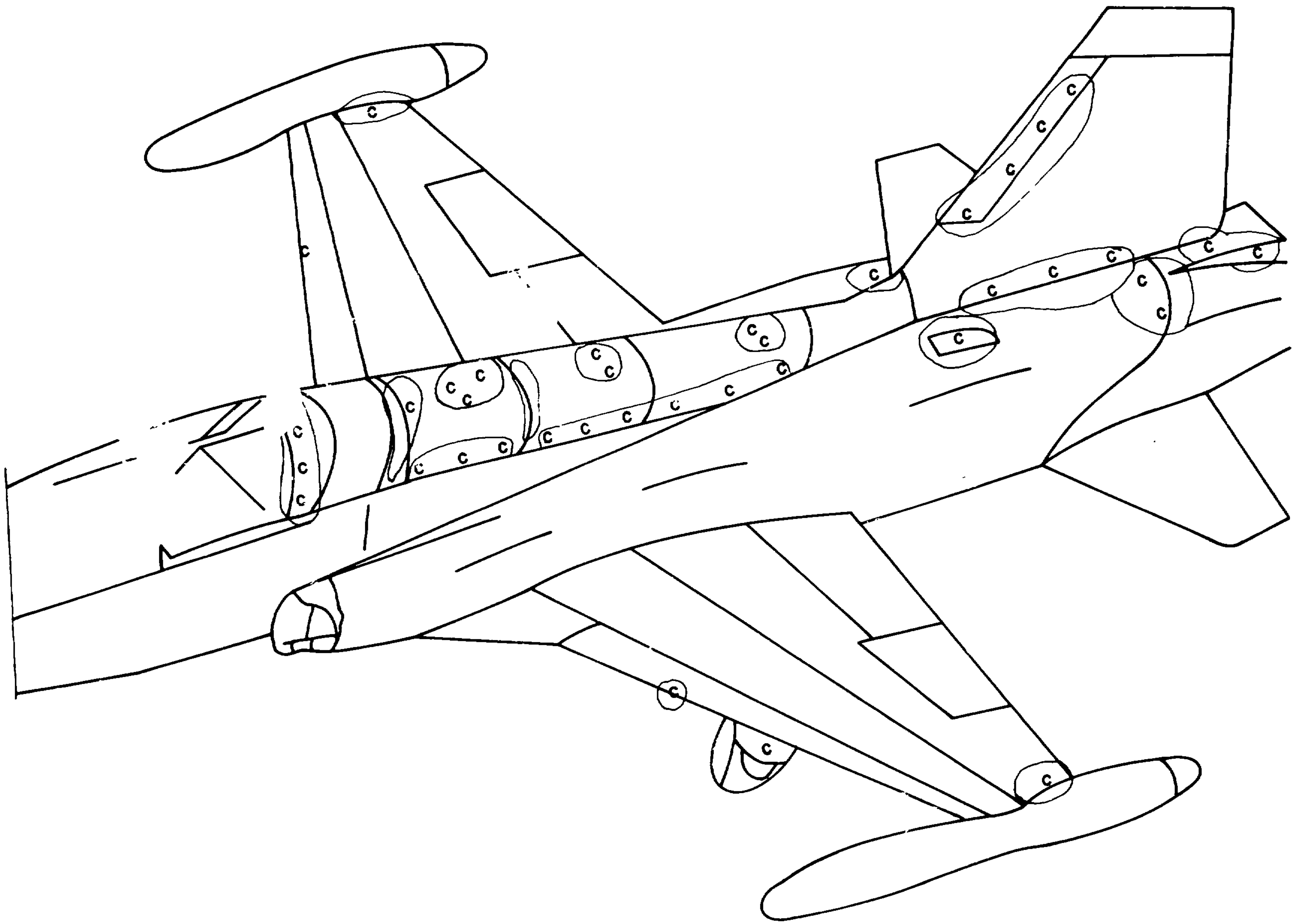


Fig.2 Locations of concentration of corrosion on the center and aft section of the aircraft body (F-5A)

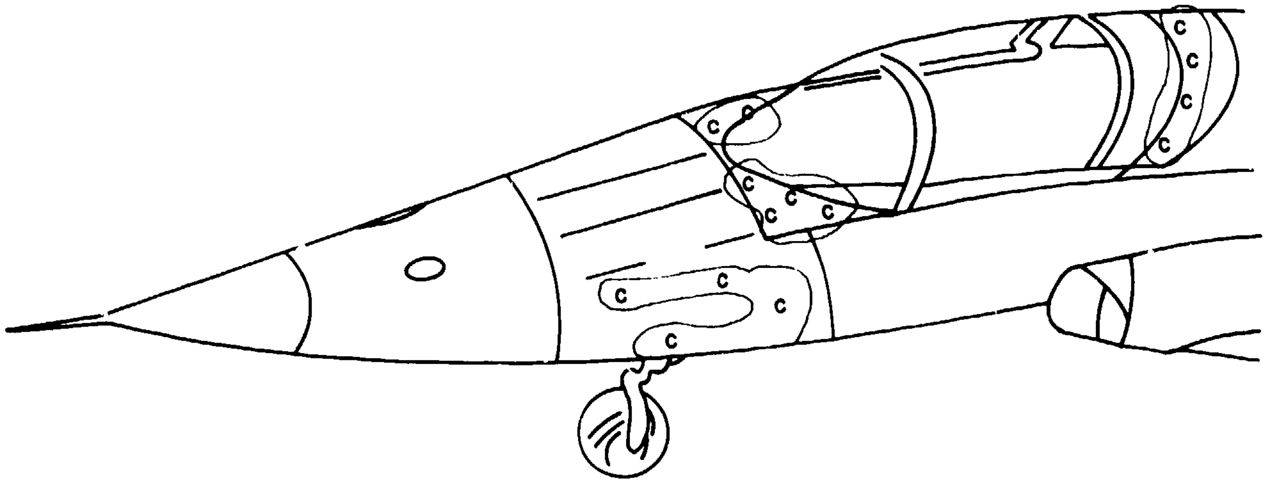


Fig.3 Locations of concentration of corrosion on the forward section of aircraft body (F-5A)

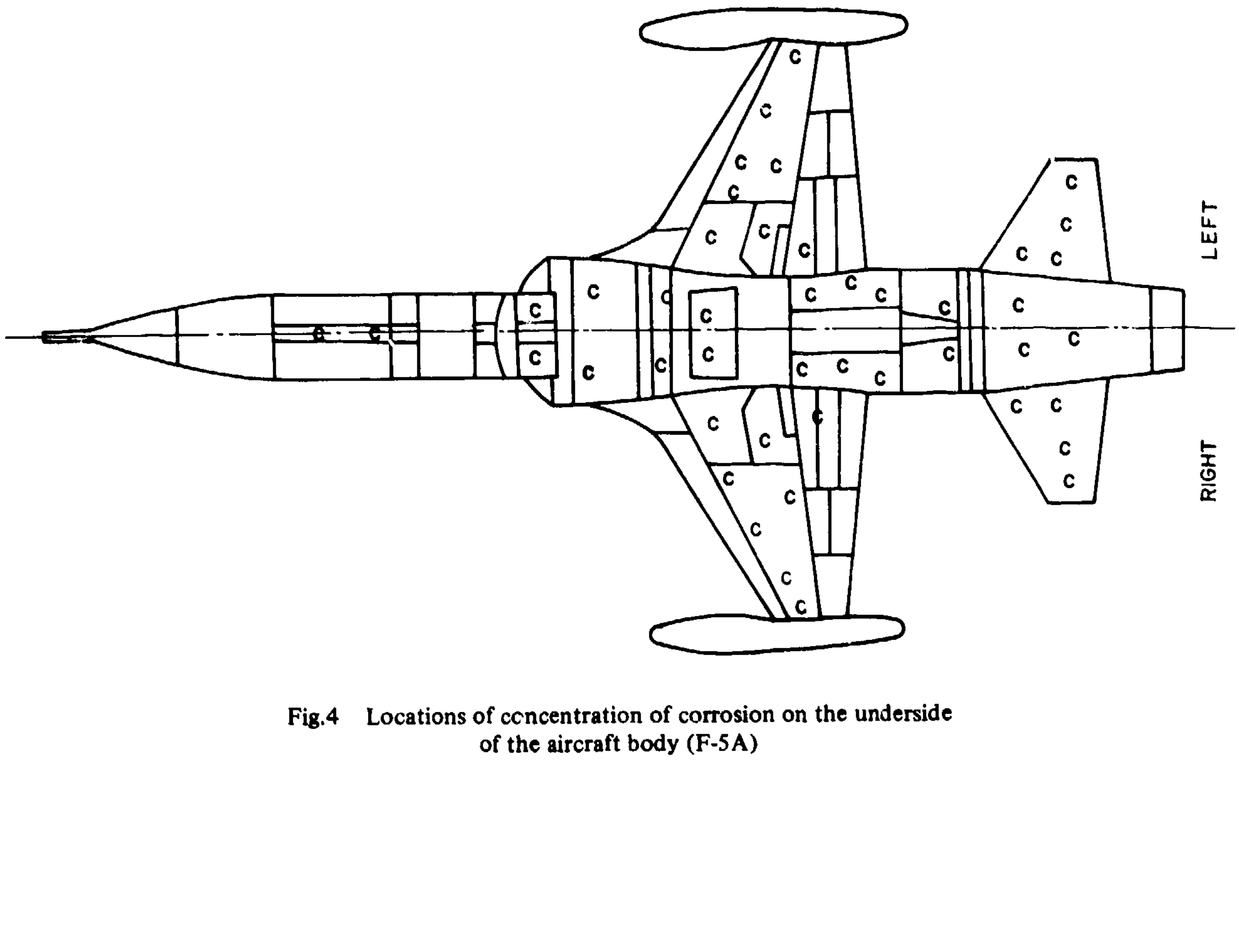


Fig.4 Locations of concentration of corrosion on the underside of the aircraft body (F-5A)

Fig.5 Damage of the vertical stabilizer attach angle through stress corrosion cracking and exfoliation (delamination goes through the full section)

Fig.6 Damage in the honeycomb assembly

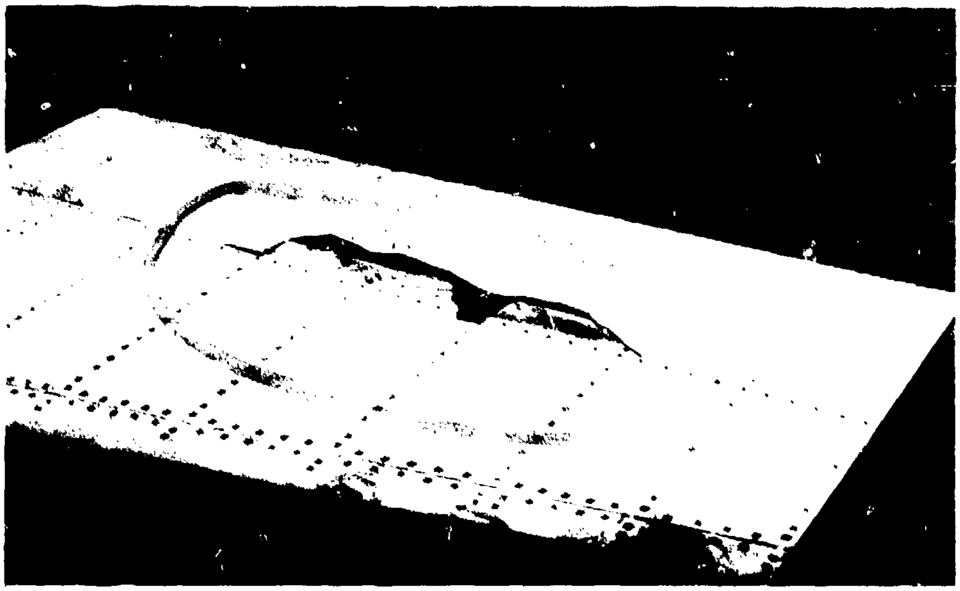


Fig.7 Tears in wings as a result of damage in the honeycomb assembly

ON THE CORROSION PROBLEMS OF THE T.A.F. F-5 AIRCRAFT

by

Capt. A.İnalhan
İstanbul Teknik Üniversitesi
Gümüşsuyu
İstanbul, Turkey

INTRODUCTION

This note comprises of some additional information about the paper presented here by Prof. Doruk, which is related to the corrosion problems of the T.A.F. F-5 Aircraft based in various locations in Turkey. In this paper, special attention is given to the effects of atmospheric conditions on the A/C in the Bandırma base and this point, in our opinion, is somewhat over-emphasised by the author. A briefaccount of the actual developments of the case and the natural conclusions drawn upon them are as follows.

THE ACTIVITIES OF EIBM ON THE CORROSION PROBLEM OF F-5 A/C

1- The problem has been discovered by the technicions of Bandırma Base, and reported to the EIBM (Eskişehir Depot Facility of T.A.F.) in March 1973, as a "painting trouble" which was what they thought it was then.

2- The EIBM team arriving in Bandırma was greatly surprised by the existence of extensive regions of corrosion in

a) The leading edge section of the vertical stabiliser (3-31414-3 P/N)
b) The attach angle which is the secondary structure joining the vertical stabiliser to the fuselage (2-31435-501, 502 P/N).
c) The wing skin at the top of the main landing gear (6-23700 P/N).
d) Main landing gear cavities.
e) Various fasteners on the wings and the fuselage.

In order to complete detailed studies on the whole of the airframe, the worst effected two aircraft have been transported to the EIBM, where a special project group was formed and carried out the following duties until 1979.

1- All F-5 aircraft of T.A.F. have been corrosion controlled and grouped accordingly into four categories, and a special weekly chech-up procedure established.

2- Various chemical and microscopic analyses have been made on a number of samples and the specific courses of corrosion (such as Galvanic, Stress,... etc) determined in almost every case at hand.

3- The main causes of the corrosion were determined to be

a) Design and production faults.
b) Insufficient knowledge of maintenance personel.
c) Atmospheric and other deterioration factors.

4- Following actions were taken accordingly.

a) The results of the project presented to the representatives of NORTHROP Inc. (USA) producer of the A/C, in a detailed briefing in E.I.B.M. and were received with interest. Also all NATO countries notified on the subject.
b) A "lead the force" program was initiated for the F-5 aircraft and also the maintenance personel have been given clear instructions on the subject.
c) Atmospheric analyses were ordered on a number of bases and in fact the values in Prof. Doruk's paper come from the reports prapared by Ankara Nuclear Research and Training Center.

CONCLUSIONS

1- The program, briefly described above has been greatly successfull and the corrosion level of F-5 A/C based in various locations in Turkey is now drastically reduced and completely under control.

2- The major cause of corrosion, in our opinion, originates in fact from the design and production faults.

3- However the maintenance errors and the atmospheric conditions have an important role in speeding up the matters.

L'EXPERIENCE DE LA CORROSION SUR AERODYNES MILITAIRES FRANCAIS

par
Melle M.Huret
SERVICE TECHNIQUE DES PROGRAMMES AERONAUTIQUES
Section Matériaux
4,avenue de la Porte d'Issy
75996 PARIS ARMEES
FRANCE

RESUME

La protection contre la corrosion des aérodynes militaires français fait l'objet, depuis 30 ans, d'une règlementation qui a évolué en fonction de l'expérience en service et des exigences croissantes de l'utilisation.

Certaines structures d'avion ont présenté une bonne résistance à la corrosion, ce comportement satisfaisant est attribué au choix de traitements et de revêtements appropriés. Au contraire, dans d'autres structures des corrosions importantes se sont manifestées, les problèmes les plus graves ont été provoqués par :
- la corrosion feuilletante des profilés,
- la corrosion des nids d'abeilles et des interfaces dans les structures collées,
- la corrosion sous tension des pièces forgées ou usinées.

L'exposé passe en revue un certain nombre de cas et en explique l'origine (insuffisance des connaissances sur la corrodabilité des structures nouvelles, gammes de protection incorrectes...). En conclusion, il est souligné que la prévention contre la corrosion doit être envisagée à tous les stades de la conception, de la fabrication et de l'entretien des aérodynes.

1. INTRODUCTION

Tous les aérodynes militaires français, utilisés par l'Armée de l'Air ou par l'Aéronavale, doivent être protégés contre la corrosion conformément à une règlementation technique établie par le Service Technique des Programmes Aéronautiques. Cette règlementation a été éditée sous forme d'une norme AIR intitulée "Instruction sur la protection des aérodynes", elle a été mise en application en 1950. Dès l'origine, son objectif principal était de faire étudier la protection anti-corrosion en même temps que le dessin des structures, elle précisait qu'un document appelé "Plan de protection" devait être établi pour chaque aérodyne. Pour faciliter la tâche des bureaux d'études, la norme rappelait les règles générales de protection des différents matériaux : ces règles étaient évidemment basées sur les connaissances de l'époque en matière de corrosion qui, en France, provenaient davantage d'études de laboratoire et d'informations documentaires que de l'expérience en service. Il faut avouer que cette règlementation a été accueillie avec réticence par les constructeurs et que les utilisateurs n'ont pas été toujours prêts à accepter les majorations de poids et de prix nécessaires pour obtenir une protection efficace. Dans certains cas, il a fallu que l'apparition de corrosions démontre la nécessité d'une protection pour que celle-ci soit acceptée.

La comparaison de la tenue en service des divers types d'aérodynes montre de grandes différences en ce qui concerne la résistance à la corrosion des structures. Pour certaines,aucune corrosion des éléments structuraux n'est apparue après plus de 15 ans d'utilisation ; pour d'autres, au contraire, la corrosion a entraîné des endommagements graves.

2. LA CORROSION DES CELLULES D'AERODYNES ET DES TRAINS D'ATTERRISSAGE

2.1. Tenue à la corrosion des structures en alliages d'aluminium.

2.1.1. Structures présentant une bonne résistance à la corrosion.

2.1.1.1. Structures à raidissage intégral.

Les voilures de nombreux avions de l'Armée de l'Air sont actuellement constituées de panneaux à raidissage intégral, usinés dans des tôles épaisses en alliage 2214 à l'état T6. La susceptibilité de cet alliage à la corrosion sous tension est connue, elle s'est d'ailleurs manifestée dans d'autres éléments dont le cas sera évoqué ultérieurement. Au contraire, dans le cas des panneaux de voilure, aucune corrosion sous tension n'a été décelée jusqu'à présent bien que certains avions soient en service depuis plus de 15 ans. Avant que les utilisateurs aient accepté la peinture complète des avions, quelques manifestations de corrosion se sont produites, sous forme de piqûres légères, sur la face externe des revêtements de voilure protégés seulement par anodisation chromique. En améliorant la qualité de l'anodisation et en appliquant un système de peinture approprié, il n'y a plus eu de problème de corrosion sur les avions de l'Armée de l'Air.

Le même type de structure a montré également une bonne résistance à la corrosion sur des avions de l'Aéronavale, malgré leur maintien permanent en atmosphère marine. Ceux-ci ont reçu dès l'origine une protection par anodisation et peinture, et il n'y a pas eu de corrosion apparente pendant plus de 10 ans. Le décapage complet de la peinture a cependant fait apparaître autour des rivets des corrosions superficielles qui paraissent se produire à partir des fissurations de la couche d'oxydation anodique.

La bonne résistance à la corrosion des panneaux en 2214 peut être attribuée :
- au dessin des pièces et à la conception des fixations ;
- au traitement mécanique qui provoque une compression de surface ;
- à l'application d'une double protection comportant oxydation anodique et peinture.

Les différentes phases de la conception des pièces et des traitements (mécaniques et électrochimiques) seront précisées dans un autre exposé.

Le système de peinture comprend trois couches :
- une couche de peinture primaire réactive (wash-primer) qui assure l'accrochage ;
- une couche de peinture primaire anti-corrosion nitrosynthétique pigmentée au chromate de zinc ;
- une couche de peinture de finition nitrosynthétique résistant aux huiles moteurs à base d'esters.

Il peut paraître surprenant que l'aviation militaire française continue à utiliser une famille de peintures qui, dans de nombreux pays, a été remplacée par des systèmes de peintures époxydiques et polyuréthannes. Le grand avantage des peintures nitrosynthétiques, pour les utilisateurs français, réside dans leur facilité d'emploi et de réparation ainsi que dans leur bonne stabilité au stockage. Par ailleurs, la formulation de ces systèmes a été bien optimisée et les spécifications appliquées sont sévères, ce qui permet d'obtenir des films ayant une bonne adhérence et un excellent pouvoir protecteur. Les critiques que peuvent susciter ces peintures sont relatives à leur résistance chimique limitée, leur farinage assez rapide, leur résistance à l'usure peu élevée et leur tenue à la température qui est à la limite des exigences des avions actuels.

Pour obtenir des protections améliorées, certains types d'avions ont été peints avec des systèmes époxy-polyuréthannes et d'autres avec des systèmes mixtes conservant les deux premières couches du système nitrosynthétique avec, en finition, une couche de peinture polyuréthanne. Les systèmes mixtes ont l'avantage d'être plus facilement décapables et réparables que les époxy-polyuréthannes, tout en présentant une résistance chimique et une résistance à l'usure nettement améliorées par rapport aux nitrosynthétiques. Jusqu'à présent, l'application des peintures polyuréthannes ne paraît pas avoir eu de répercussion sensible sur la résistance à la corrosion des structures en alliage 2214 anodisé, sauf sur un avion de l'Aéronavale, peint à titre d'essai en système mixte, où le remplacement de la finition nitrosynthétique par une finition polyuréthanne a fait apparaître autour des rivets de la corrosion filiforme. D'une manière générale, il a été constaté une moins bonne adhérence des polyuréthannes sur les têtes de vis et sur les rivets, ce qui peut augmenter les risques de corrosion de ces éléments et des zones de structure limitrophes.

Actuellement l'expérimentation des systèmes polyuréthannes est orientée vers les systèmes développés pour l'aviation civile afin de lutter contre la corrosion filiforme, ils comportent une finition polyuréthanne souple sur une peinture primaire réactive et une peinture anti-corrosion permettant de réduire, sinon d'éliminer totalement, les attaques de corrosion filiforme ; de toutes façons, la meilleure adhérence de ces systèmes, sur les éléments de fixation et les jonctions, constitue un avantage important des finitions polyuréthannes souples.

2.1.1.2. Structures rivées en alliages d'aluminium plaqués.

Dans les structures rivées, les alliages d'aluminium plaqués ont eu, en général, une bonne tenue au cours des 15 dernières années, c'est-à-dire depuis que les extérieurs de tous les aérodynes militaires sont peints. Auparavant, des cas de corrosion importante ont été fréquents sur les revêtements plaqués qui, pour avoir un comportement satisfaisant, auraient dû être entretenus fréquemment en utilisation, ce qui s'est avéré difficile à réaliser. Lorsque la corrosion avait détruit des surfaces notables de placage, l'attaque de l'âme en alliage 2017A pouvait alors se développer rapidement. Actuellement, il reste très peu de structures non peintes, ce sont, par exemple, des intérieurs de manches à air où la corrosion par piqûres demeure limitée, la protection par peinture y est d'ailleurs de plus en plus étendue.

La résistance à la corrosion des tôles plaquées protégées par le système nitrosynthétique a donc été satisfaisante sauf dans quelques cas où l'application avait été défectueuse. La situation a changé lorsque les finitions nitrosynthétiques ont été remplacées par des finitions polyuréthannes sur certains avions de l'Aéronavale : la corrosion filiforme est alors apparue sur les appareils basés en permanence dans des lieux où le degré hygrométrique se maintient constamment à 80% ou au-dessus. Par contre, les avions du même type effectuant les mêmes missions, mais stationnés sur des bases où l'hygrométrie est moins élevée, n'ont pas présenté ce phénomène.

La corrosion filiforme est à rapprocher des corrosions de zones interfaciales dans les structures en alliage plaqué soudées et surtout dans les structures collées, ces corrosions se produisent toutes dans des atmosphères confinées où l'humidité peut stagner.

2.1.2. Structures ayant donné lieu à des problèmes de corrosion importants.

2.1.2.1. Structures collées.

Les problèmes de corrosion des structures collées seront relatés de façon plus détaillée que ceux relatifs aux autres formes graves de corrosion (feuilletante, sous tension) car, pour celles-ci, l'expérience sur aérodynes militaires français semble être analogue à celle des autres forces aériennes. Au contraire, l'utilisation par l'Aéronavale d'avions à structure presque totalement collée a posé des problèmes importants, il paraît utile d'en faire connaître l'origine ainsi que les moyens mis en oeuvre pour y remédier.

La première expérience française d'avion métallique collé n'a cependant pas laissé entrevoir les problèmes qui sont apparus ultérieurement, il s'agissait d'un avion d'armes à voilure collée mis en service en 1955. Sa conception était celle d'un raidissage par lisses collées sur le revêtement en tôle d'alliage 2017 A non plaquée ; l'adhésif était de nature époxydique et fabriqué par la Société CIBA sous la référence "ARALDITE Type I", il avait la particularité de se présenter sous forme de bâtons et d'être applicable par fusion au contact de la tôle préchauffée, la polymérisation se faisait ensuite par chauffage sous faible pression. En dehors de la voilure, les autres éléments collés étaient des trappes de train et des portes, leur structure "sandwich" comportait une âme en nid d'abeilles d'alliage 5052 perforé, assemblée avec les revêtements au moyen d'un adhésif en film.

Les avions de ce type ont été réformés, après une vingtaine d'années d'utilisation, sans que la tenue des collages de voilure ait posé de problèmes : ni décollements, ni corrosion dans la tôle n'ont été constatés ; il y a lieu de remarquer que ces structures constituaient des réservoirs à carburant et qu'elles étaient, de ce fait,protégées de l'action de l'atmosphère environnante. Au contraire des éléments collés, les profilés rivés en alliage 2214 consituant les longerons ont présenté d'importantes corrosions (cf § 2.1.1.2. sur la corrosion feuilletante). Sur les éléments en structure sandwich, aucune corrosion des nids d'abeilles ne s'est produite car ils avaient été protégés par vernis : ce vernis avait été appliqué pour renforcer la résistance des joints nodaux et non pour protéger le métal car, à l'époque, l'on n'imaginait pas que la corrosion puisse se produire à l'intérieur d'un panneau étanché par le film adhésif. Cette protection involontaire a eu un effet favorable pour l'avion concerné mais a masqué un phénomène qui, s'il s'était révélé au début des années 60, aurait été connu avant que soit lancée la fabrication d'un avion de surveillance marine à structure sandwich.

Le choix d'une structure collée de type sandwich, au lieu des structures conventionnelles, était motivé par les avantages suivants :
- meilleure tenue au flambage permettant un gain de poids ;
- meilleure tenue en fatigue ;
- bonne résistance aux vibrations aérodynamiques et acoustiques.

La bonne tenue en fatigue et la qualité fail-safe de la structure ont été vérifiées au cours de l'essai de la cellule de fatigue de cet avion : en effet, une crique, initiée sur la peau extérieure d'un panneau intrados de voilure, n'a évolué que très lentement (elle est passée de 0,5 à 1 m en 2000 heures de vol simulé) et la peau intérieure est restée intacte. Ce bon comportement en fatigue a d'ailleurs été confirmé par l'expérience en service. Malheureusement si les endommagements en fatigue ont été évités, ceux provoqués par la corrosion ont pris une importance qui a surpris constructeurs et utilisateurs.

Corrosion des nids d'abeilles métalliques

A l'époque de la conception de l'avion, c'est-à-dire vers 1960, les constructeurs européens avaient eu connaissance de certaines corrosions, survenues aux Etats-Unis, sur les structures en nid d'abeilles perforé et savaient que l'industrie américaine s'orientait vers le nid d'abeilles non perforé. Par ailleurs, les alliages aluminium-magnésium avaient la réputation de bien résister à la corrosion et l'introduction d'humidité à l'intérieur de panneaux sandwich encadrés de bordures collées semblait improbable. En conséquence, les nids d'abeilles choisis pour la fabrication de série étaient en alliage 5052 non perforé et sans protection.

Environ 30 mois après la mise en service des avions, les premières altérations de nids d'abeilles ont été constatées sur des éléments non ou peu travaillants où les épaisseurs de clinquant étaient les plus faibles ; il s'agissait, en particulier, d'éléments de bord d'attaque et de portes situées à la partie inférieure du fuselage. Les endommagements se manifestaient par l'enfoncement des revêtements sous la simple pression du doigt, les dissections de ces éléments ont montré que l'altération du clinquant allait d'un léger ternissement jusqu'à la désagrégation totale, la présence d'eau dans les cellules a été également constatée.

A la suite de ces constatations, diverses actions furent lancées pour, d'une part, prendre des mesures immédiates pour la sauvegarde des avions, et d'autre part, comprendre le phénomène de corrosion et déterminer les moyens de l'éviter à l'avenir. En premier lieu, il a fallu trouver une technique de contrôle non destructif afin de détecter sur avion les zones corrodées ou contenant de l'eau. Après diverses tentatives, des procédures de contrôle par ultra-sons ont pu être mises au point et ont permis, dans l'ensemble, d'établir des cartographies précises des endommagements. En raison du travail considérable que représente l'auscultation de grandes surfaces, la détection a d'abord été effectuée sur les éléments comportant des nids d'abeilles de faible épaisseur, le nombre de zones à contrôler a été progressivement augmenté au fur et à mesure que des inspections plus complètes, faites par les réparateurs, mettaient en évidence des anomalies sur de nouvelles zones. Bien entendu, il a fallu réaliser les étalonnages nécessaires des appareils de contrôle avec des éprouvettes-témoins de constitution identique à celle des zones à contrôler et assurer la formation de personnel compétent chez les utilisateurs comme chez les constructeurs et réparateurs. Contrairement à une hypothèse faite à partir des premières constatations, la corrosion ne s'est pas limitée au clinquant de 25 µm, elle a atteint aussi ceux de 40 µm et plus ; il y a seulement une différence dans les vitesses de développement du phénomène.

Etude et reproduction du phénomène de corrosion

Un grand nombre d'études et essais ont été effectués pour analyser le phénomène et le reproduire en laboratoire sur des éprouvettes dont certaines atteignaient les dimensions d'un panneau réel.

Des prélèvements de gaz, liquides et solides, effectués dans les cellules de nids d'abeilles corrodés ont montré que :
- les gaz contenaient une très forte teneur en hydrogène dans les zones corrodées (35 à 40% et même parfois 75%) et une diminution de l'oxygène par rapport à l'azote ;
- les liquides avaient un pH alcalin pouvant atteindre 9, ils contenaient un peu de chlore mais dans une proportion semblable à celle d'une eau de ville ;
- les solides, d'après les analyses chimique et cristallographique, paraissaient constitués d'hydroxyde d'aluminium, d'hydroxyde de magnésium et d'aluminate de magnésium.

Les essais classiques de corrosion par brouillard salin ne mettant pas bien en évidence la corrodabilité du clinquant, une méthode d'essai particulière a été mise au point : elle consistait à mettre en contact des fragments de nid d'abeilles avec de l'eau distillée en atmosphère confinée en agitant le tout. Les prélèvements gazeux faits dans l'atmosphère, au-dessus du liquide, ont montré la présence d'hydrogène après 150 heures à une température de 20°C et après 30 heures dont 15 à 20°C et 15 à 45°C. Les prélèvements, effectués après que le nid d'abeilles ait présenté une corrosion prononcée, ont montré que gaz, liquides et solides avaient des compositions voisines de celles des produits prélevés sur avion. Ces essais ont confirmé que, même en l'absence de sel, l'eau pouvait attaquer très rapidement les alliages aluminium-magnésium en atmosphère confinée ; le taux d'écrouissage important des clinquants a vraisemblablement aggravé le phénomène.

D'autres essais ont permis de reproduire également l'attaque du clinquant mais d'une manière plus progressive, ce sont :
- l'essai d'immersions alternées dans l'eau de mer artificielle (pH=8) suivant NF A 91-411 ;
- l'essai d'injection de solutions à pH=8 (ou autres) dans des petits panneaux sandwich représentatifs de la structure avion, il a été effectué à 70°C et avec agitation afin d'accélérer le phénomène.

Choix des protections de nid d'abeilles

Les mêmes essais ont permis de sélectionner des protections du clinquant et, en premier lieu, un vernis qui a amélioré très notablement la résistance à la corrosion : la durée au bout de laquelle était détectée la corrosion passait de 40 h pour le nid d'abeilles sans protection à 1000 h avec vernis. Etant donné l'urgence des mesures à prendre pour éviter la corrosion des avions restant à fabriquer, l'application du vernis après expansion du nid d'abeilles a été immédiatement adoptée en production. Des essais ont été effectués aussi avec des protections par conversion chimique qui ont donné des résultats irréguliers puis avec des doubles protections : conversion chimique sur le clinquant avant collage puis vernissage du nid d'abeilles après expansion, ces dernières protections ont donné les meilleurs résultats.

Amélioration de l'étanchéité des structures sandwich

L'injection d'eau dans le nid d'abeilles a pu permettre de reproduire le phénomène de corrosion, par contre l'introduction de l'eau dans les panneaux n'a pu être reproduite sur des panneaux soumis à des variations de température et de pression suivant des cycles représentant le vol de l'avion. L'hypothèse de la pénétration de la vapeur d'eau sous l'influence des différences de pression et de sa condensation par suite des variations de température reste plausible ; néanmoins il est probable que l'eau s'est aussi infiltrée sous forme de liquide : sur la voilure les endommagements paraissent maintenant beaucoup plus fréquents à l'extrados qu'à l'intrados.

Sur la presque totalité des avions construits avant qu'apparaissent les premières corrosions, la présence de liquide a été constatée même dans les plans centraux où le nid d'abeilles est le plus dense. En même temps que la protection par vernis était adoptée, de nombreuses modifications destinées à améliorer l'étanchéité étaient mises en application. Les possibilités d'étanchéification étant fonction de la conception des assemblages, il n'a pas été toujours possible de trouver des solutions sûres, d'autant plus que la durabilité des produits d'étanchéité dépend des conditions d'environnement et des efforts subis en vol. Néanmoins, sur les avions qui ont pu bénéficier, en fabrication, de l'ensemble des mesures améliorant l'étanchéité , les contrôles aux ultra-sons ne font pas apparaître la présence de liquide même après plusieurs années.

Réparation des structures collées

Les problèmes les plus difficiles à résoudre ont été ceux de la réparation des avions corrodés. Pour les éléments mobiles, la réparation a eu surtout pour objectif d'atteindre un certain potentiel et de remplacer l'élément à partir du moment où les critères d'endommagement atteignaient un seuil critique pour la résistance. Pour le fuselage et la voilure, les réparations ont nécessité la mise au point de techniques appropriées et se sont heurtées à beaucoup de difficultés : le principe de réparation a été la trépanation des zones corrodées en suivant les cartographies établies par contrôle aux ultra-sons puis la mise en place d'un pain de nid d'abeilles neuf protégé, en étanchéifiant soigneusement les zones de bordure. Ce type de réparation s'est heurté à des difficultés inhérentes :
- aux caractéristiques des adhésifs polymérisables à température ambiante ou ne dépassant pas 60° ;
- à la préparation des surfaces à coller ;
- à la mise en pression des collages de grandes dimensions pendant le temps nécessaire à la polymérisation de l'adhésif.

Les études effectuées sur les adhésifs structuraux polymérisant à basse température ont montré que leurs résistances au pelage étaient très inférieures à celle des adhésifs d'origine polymérisés à 170°C. La tenue au vieillissement humide est aléatoire et dépend, en particulier, de la température atteinte pendant la polymérisation, d'où la mauvaise tenue de certaines réparations. Les difficultés de préparation de surface et d'accostage correct ont été aussi à l'origine de décollements qui ont conduit à refaire à nouveau le collage. Tous ces problèmes ont eu au moins l'avantage de mettre en évidence la bonne tenue du nid d'abeilles (protégé par vernis) mis en place à la première réparation et ceci même lorsque des quantités d'eau importantes s'étaient infiltrées.

Les utilisations de nid d'abeilles non protégé ont été peu nombreuses sur les avions de l'Armée de l'Air, elles ont également donné lieu à des corrosions, en particulier dans les planchers d'un avion de transport. Dans ce cas, l'étanchéité de bordure avait été particulièrement mal conçue et réalisée et les endommagements ont été plus importants que ceux des éléments similaires de l'avion de surveillance marine.

Corrosion des interfaces de collages métal-métal

En dehors de la corrosion des nids d'abeilles, un autre grave problème a été celui du collage des interfaces métal-métal ; il est apparu plus tard, au bout de 4 ans environ, et a affecté d'abord les ailes extrêmes. Par suite de la pénétration d'humidité dans les joints collés, le placage se corrode sous l'adhésif et progressivement la corrosion détruit complètement le collage. Les zones touchées étaient celles collées avec l'adhésif FM 1000, qui avait été choisi à cause de ses propriétés mécaniques nettement supérieures à celles de l'adhésif FM 61 utilisé dans les collages sandwich. Les essais de qualification de FM 1000 avaient cependant montré une très forte chute des caractéristiques en milieu humide, mais cet essai, qui figurait déjà dans les normes AIR relatives au collage, avait été jugé trop sévère et non représentatif de la réalité... L'utilisation de FM 1000 avait été finalement admise à condition que les joints collés soient très bien protégés pour les soustraire à l'action de l'humidité ; en fait, cette condition n'a pas été remplie car la conception des bordures de panneaux et des renforts ne permettait pas de réaliser un cordon d'étanchéité suffisamment adhérent. L'endommagement en service des produits d'étanchéité (par vieillissement et arrachement) nécessite en outre un entretien permanent qui est difficilement réalisable sur un gros avion.

Lorsque les premières corrosions d'interface ont été décelées, l'adhésif FM 1000 a été remplacé par l'adhésif FM 61 sur les structures qui étaient encore en fabrication et certains éléments ont pu être traités par anodisation chromique (non colmatée) avant collage. L'étanchéité a été améliorée et, en particulier, les jonctions de panneaux ont été protégées par des couvre-joints montés avec interposition de produits d'étanchéité.

Pour les avions en utilisation, il a fallu mettre au point des techniques de réparation permettant de conserver aux structures une résistance suffisante. Sur les voilures où les décollements dépassaient une certaine surface, il fallut enlever la tôle corrodée et la remplacer par une tôle neuve collée avec un adhésif polymérisant à basse température. Pour traiter des stades moins avancés de décollement, une méthode d'injection directe dans le joint a été utilisée ; l'injection est faite à partir de la bordure du joint partiellement décollé, le premier produit injecté est une solution de bichromate de potassium destinée à neutraliser la corrosion, après séchage à l'air chaud un produit d'étanchéité est injecté. Des essais de corrosion par immersions-alternées ont montré l'efficacité du traitement et, sur avions, un ralentissement de la progression de la corrosion a été constaté. Néanmoins, au bout de quelques années il est de plus en plus souvent nécessaire de réparer par trépanation et remplacement des tôles corrodées.

2.1.2.2. Structures comportant des éléments sensibles à la corrosion feuilletante.

La corrosion feuilletante des alliages aluminium-cuivre (2017 A, 2024) a été constatée sur de nombreux aérodynes. Les corrosions les plus graves pour la résistance des structures ont été celles des plans centraux de certains avions de transport anciens dont il a fallu remplacer les panneaux extrados en raison de la corrosion profonde des lisses. Ce type d'avion a été mis en service à partir de 1953, les causes et les conditions de développement des corrosions feuilletantes étaient alors mal connues.

Les lisses de plans centraux ont un profil en omega et une grande longueur, il est donc difficile d'en explorer l'intérieur et de nombreux démontages sont nécessaires avant d'atteindre cette zone de l'avion. Dans une première définition, ces lisses étaient obtenues par pliage de tôles en alliages 2017 A plaqué, elles étaient anodisées (en milieu sulfurique) avant rivetage sur le revêtement lui-même plaqué et anodisé. A l'époque, la norme AIR 7521* n'imposait pas la double protection pour les avions de l'Armée de l'Air et il n'y eut pas d'application de peinture après montage. Après les essais statiques de la cellule un renforcement des lisses s'était avéré nécessaire et avait été fait par adjonction d'une baguette de renfort en 2017 A filé également anodisée avant rivetage. Cette solution de renforcement ayant été jugée onéreuse, les lisses avec renfort furent remplacées par des profilés de même forme en alliage 2024/T3 à partir du 2ème tiers de la série. Ultérieurement, en raison de l'évolution des connaissances sur la corrosion des alliages d'aluminium filés, il a été décidé d'appliquer de la peinture à l'intérieur et à l'extérieur des lisses mais la peinture intérieure n'a pu être faite sur les panneaux déjà assemblés ; la peinture complète des lisses n'a donc été effectuée en fabrication que pour les derniers avions (30% environ de la série).

Les premières détections de corrosions sur les lisses furent faites 5 à 6 ans après la mise en service des avions mais l'importance de la corrosion ne fut reconnue que sur un avion ayant alors 10 ans d'utilisation. L'examen d'autres avions montra la gravité des endommagements et aboutit d'abord à une interdiction de vol momentanée puis à la décision de changer les panneaux d'intrados sur les 2/3 des avions. La corrosion intérieure ne se manifestait souvent que par de faibles corrosions à l'extérieur des lisses alors que la corrosion feuilletante était très importante à l'intérieur et risquait de compromettre la résistance de la structure. Depuis le changement des panneaux, la tenue des lisses n'a pas posé de problèmes, seules quelques corrosions par piqûres sont apparues récemment. Il y a lieu de remarquer que :

- les panneaux où les lisses pliées étaient peintes ont eu une tenue assez satisfaisante ;
- l'entretien des avions est probablement meilleur qu'il n'avait été en début de série.

A l'origine de ce grave problème de corrosion se trouvent des erreurs commises par insuffisance de connaissances sur la corrodabilité de l'alliage et par méconnaissance des risques de corrosion entraînés par les condensations et infiltrations dans des zones non visitables. En outre, les constructeurs et les utilisateurs avaient une confiance exagérée dans la protection apportée par l'anodisation et, contrairement à l'avis des spécialistes de corrosion, il leur paraissait inutile de faire la dépense supplémentaire de la peinture.

Dans d'autres zones des mêmes avions, des corrosions importantes se sont produites, surtout sous l'action de liquides provenant des installations toilettes ; dans ces zones la réparation ou le changement local des éléments corrodés n'a pas posé de problème, l'accessibilité étant satisfaisante. Des corrosions de longerons arrière ont pu aussi être traitées efficacement.

* Instruction sur la protection des aérodynes.

Sur un autre type d'avion de transport de l'Armée de l'Air, qui a été mis en service en 1967, l'expérience acquise sur le précédent a conduit à utiliser de préférence des alliages à l'état T6, néanmoins certaines pièces sont encore en alliages à l'état T3 en raison de considérations relatives à la fatigue. Des corrosions importantes de ces alliages ont été détectées après 5 ou 6 ans d'utilisation dans l'arrière du fuselage, en particulier du côté qui reçoit des suintements de liquides en provenance des installations toilettes. Les longerons d'empennage horizontal commencent aussi à présenter des corrosions intergranulaires localisées.

Le principe de la double protection avait été très discuté par les constructeurs de cet avion, il a été finalement admis pour certaines zones, parties basses du fuselage en particulier, alors que les premiers avions étaient déjà en fin de chaîne de montage. Le primaire époxydique qui doit protéger les surfaces intérieures a donc été appliqué après assemblage dans des conditions peu favorables à une bonne tenue. Par ailleurs, des motifs d'ordre économique avaient laissé admettre, pour certains éléments, le choix entre traitement de conversion chimique (chromatation) et anodisation ; dans ces conditions sévères de corrosion, la protection par conversion chimique + primaire époxydique peut être insuffisante. Bien que, dans l'ensemble, la protection de ce type d'avion soit nettement améliorée par rapport au précédent, les réticences des constructeurs à admettre le coût d'une protection efficace ont été encore à l'origine des corrosions.

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Sur les avions d'armes de l'Armée de l'Air, actuellement en service, les cas de corrosion feuilletante ont été très rares puisqu'ils ne comportent qu'un petit nombre d'éléments sensibles à ce type de corrosion.

La protection par anodisation + système de peinture nitrosynthétique protège efficacement l'alliage 2024 à l'état T3 mais quelques corrosions se sont parfois produites à partir de trous de rivets fraisés après anodisation. Une diminution sensible des corrosions a d'ailleurs pu être obtenue en modifiant le traitement thermique du 2024 et en complétant la protection par une interposition de mastic inhibiteur sous la tête des rivets.

Parmi les avions anciens, ceux à voilure collée ont présenté des corrosions importantes de longerons en alliage 2024 après des durées d'utilisation de l'ordre de 15 à 20 ans, bien que les endommagements aient été importants et systématiques les mesures prises ont surtout eu pour but de limiter et de surveiller l'évolution des corrosions jusqu'à ce que les avions aient atteint leur limite de potentiel. Pendant cette période, les corrosions ont paru progresser rapidement mais il est possible que cela soit la conséquence d'une amélioration de la technique de détection des corrosions par ultra-sons.

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Sur les avions de l'Aéronavale, les corrosions feuilletantes ont été nombreuses dans toutes les zones pouvant retenir l'eau de condensation ou de ruissellement : en particulier dans les parties basses du fuselage, à l'arrière des voilures et sur les empennages. Comme sur les avions de l'Armée de l'Air, la protection par anodisation et peinture a été généralement efficace mais les corrosions sont parties des trous de rivets fraisés après anodisation.

2.1.2.3. Structures comportant des éléments sensibles à la corrosion sous tension

La corrosion sous tension de l'alliage 2024 à l'état T351 a été constatée surtout sur des avions utilisés en atmosphère marine. Les éléments atteints étaient des ferrures situées soit à l'arrière de la voilure, soit sur l'empennage, ces ferrures avaient été usinées dans le sens travers court de profilés et comportaient des trous d'articulation bagués. L'emmanchement à force des bagues dans l'alliage 2024 non protégé provoquait des contraintes permanentes qui, à leur tour, induisaient des criques dans l'alésage. Lorsqu'il n'a pas été possible de changer l'alliage ou de modifier le plan de prélèvement des ferrures, diverses mesures ont pu améliorer la tenue en service :
- protection des alésages et revêtement des bagues ;
- remplacement de l'emmanchement à force des bagues par un collage ;
- application de mastic d'étanchéité sur le pourtour des bagues.

D'autres cas de corrosion sous tension se sont produits sur des caissons d'atterrisseurs en alliage 2214 à l'état T6, forgé ou matricé. Bien que ces pièces ne fassent pas partie de la structure de l'avion, leur fissuration entraîne l'application de procédures de surveillance, contrôles et réparations aussi pénalisantes pour les utilisateurs que s'il s'agissait d'éléments structuraux.

Des criques de corrosion sous tension ont été constatées, en particulier, sur les atterrisseurs d'un avion de surveillance marine et sur ceux d'un avion de transport de l'Armée de l'Air, les atterrisseurs de ce dernier sont placés dans un environnement peu différent du milieu marin car ils sont logés dans des nacelles qui retiennent l'humidité. Les criques se sont initiées dans des zones soumises à des contraintes dues au chemisage ou à l'emmanchement à force de bagues ou de roulements, ces contraintes permanentes s'ajoutent à celles provoquées par le poids de l'avion et le fonctionnement de l'atterrisseur ; en outre, il est possible que des tensions internes aient parfois joué un rôle dans le déclenchement du phénomène. Les criques se sont produites après des durées variables, les premières détections ont été généralement faites 2 à 3 ans après la mise en service de l'avion ; le pourcentage de caissons criqués a été plus important pour l'avion de l'Armée de l'Air que pour celui de l'Aéronavale : 75% environ pour le premier et 35% pour le second. Plusieurs dissections de pièces ont montré que la zone d'initiation des criques présentait toujours un faciès intergranulaire et voisinait avec des piqûres de corrosion, parfois l'initiation s'est faite sur un angle vif, dans d'autres cas l'examen métallographique a montré un fibrage marqué et l'effet de travers a pu être important.

Tous ces caissons exposés à des ruissellements et à des condensations étaient protégés par peinture à l'extérieur mais, à l'intérieur, ils n'avaient, au mieux, qu'une protection par conversion chimique (chromatation). Les premières mesures prises pour réparer les caissons ont comporté l'application de primaires ou de mastic anti-corrosion dans les alésages. La protection et l'étanchéité des atterrisseurs ont été ensuite entièrement réétudiées, les caissons sont traités maintenant par grenaillage à la bille de verre suivi d'une anodisation en milieu chromique. L'interposition de mastics anti-corrosion est effectuée chaque fois que les conditions d'emmanchement le permettent et des cordons de mastics à base d'élastomères sont appliqués sur les jonctions. En outre des boîtiers de protection contre le ruissellement ont été placés en certaines zones. Ces mesures semblent avoir été efficaces car, depuis 4 ans, la présence de criques n'a été décelée que sur deux atterrisseurs de l'avion de l'Armée de l'Air. Pour ce dernier, cependant, un changement d'alliage avait été prévu dès le début des incidents et l'alliage 2214 a été remplacé par le 7009 sur les derniers atterrisseurs mis en service.

2.2. Tenue à la corrosion des autres métaux

2.2.1. Aciers

La corrosion de la visserie et des raccords en acier est un problème irritant pour les utilisateurs qui le voient apparaître même sur des avions ayant peu d'heures de vol. En principe, ces éléments doivent recevoir une double protection qui, d'une manière générale, comporte un cadmiage suivi d'une peinture.
Les tolérances dimensionnelles imposées à la visserie ne permettent cependant pas d'appliquer une épaisseur de cadmium suffisante pour obtenir une bonne protection, de plus les conditions de traitement de pièces de petites dimensions ne favorisent par la formation d'une couche d'épaisseur régulière. La tenue de la peinture sur les têtes de vis constitue aussi un problème mal résolu : pour que l'adhérence soit bonne, le nettoyage avant peinture devrait être parfait, cela n'est pas toujours possible dans des conditions de production où la durée de chaque opération doit être réduite au strict minimum ; en outre certaines peintures trop rigides s'écaillent au premier démontage, même si elles ont été bien appliquées En général, les corrosions de vis en aciers de résistance moyenne ne compromettent pas la résistance des assemblages, mais le contact de l'acier corrodé peut provoquer des corrosions importantes des alliages d'aluminium et surtout des alliages de magnésium. Les corrosions les plus graves sont celles des aciers à haute résistance utilisés pour la boulonnerie, des ruptures de boulons en corrosion sous tension ont été parfois constatées. La réalisation de protections efficaces est particulièrement difficile pour les boulons d'attache d'ailes situés dans les alvéoles de ferrures piano car, à l'extrados, ces alvéoles peuvent recueillir les eaux de pluie ou de lavage ; le montage avec interposition d'un mastic inhibiteur de corrosion et une bonne peinture sur les têtes de boulons sont indispensables, en outre il est souvent nécessaire de prévoir une protection complémentaire isolant les boulons du contact permanent avec l'eau.

Les pièces mécaniques présentent souvent des corrosions dues au frottement et à l'absence de protection car les tolérances d'ajustage et les conditions de fonctionnement ne permettent pas d'appliquer une protection efficace. Le graissage doit, en principe, jouer le rôle de protection mais la conception des pièces et leur emplacement ne permettent pas toujours d'assurer un graissage permanent ; en outre, certaines graisses synthétiques présentent l'inconvénient de devenir corrosives pour l'élément à protéger, cela a été constaté, en particulier, avec des graisses à base d'esters contenant du bisulfure de molybdène.

En dehors de la visserie et des pièces mécaniques, quelques problèmes de corrosion sont apparus dans des éléments tubulaires où la protection intérieure a été souvent négligée. Un autre problème difficile à résoudre est celui de rails sur lesquels frottent des galets, l'usure des revêtements protecteurs est rapide et nécessite un entretien constant.

2.2.2. Alliages de magnésium.

La corrodabilité des alliages de magnésium est, malheureusement, bien connue et elle a causé de nombreux endommagements sur les aérodynes militaires français; les plus fréquents ont été dûs à des corrosions intergranulaires initiées autour de bagues en acier ou en bronze.Sur des pièces recevant des chocs en service, les roues par exemple, la corrosion peut partir des points d'impact et progresser rapidement si les utilisateurs ne font pas de retouches locales de protection.

Il y a cependant des pièces en magnésium qui ont un comportement à peu près satisfaisant en utilisation. Sur les avions d'armes, des aérofreins et des trappes présentent parfois quelques piqûres mais celles-ci sont éliminées facilement par meulage et restent dans les limites tolérées, ces éléments sont protégés par mordançage et par le système de peinture nitrosynthétique standard renforcé cependant par une couche supplémentaire.
L'efficacité d'une protection bien conçue a été également démontrée sur certains éléments de l'avion de surveillance marine , qui a été mentionné précédemment à propos des corrosions de structures collées et des corrosions feuilletantes. Or, sur cet avion, les socles pilotes en alliage de magnésium n'ont présenté qu'un seul cas grave de corrosion qui a d'ailleurs été attribué à une réalisation incorrecte de la protection ; celle-ci est constituée par un système de peinture époxydique polymérisé à 180-200°C, il est appliqué sur mordançage et après colmatage par immersion dans un vernis de même nature. L'influence de la protection est encore plus évidente lorsque l'on compare la tenue en service de ces socles avec ceux, de forme semblable, montés sur des avions de transport de l'Armée de l'Air : sur ceux-ci de nombreuses corrosions ont été constatées et ont entraîné un rebut important, dans ce cas les protections ont été mal conçues et mal réalisées, en particulier des éléments de fixation en acier cadmié ont été montés dans le magnésium sans isolement suffisant.

3. LA CORROSION DES ORGANES DE PROPULSION ET DES EQUIPEMENTS

3.1. Moteurs

Les problèmes de corrosion sur les moteurs se présentent très différemment de ceux des cellules en raison de la multiplicité des matériaux utilisés ainsi que de la diversité des conditions de fonctionnement et d'utilisation ; il n'est donc pas possible d'examiner en détail ces problèmes dans le cadre du présent exposé.

Les principes de double protection et d'interposition dans les assemblages peuvent rarement être appliqués aux moteurs. Certaines corrosions d'interface ont pu être évitées par l'interposition de graisses silicones contenant des chromates mais l'efficacité est limitée en température. L'amélioration de la résistance à la corrosion des moteurs suscite en permanence des études dans le domaine des protections hautes températures.

Par ailleurs, les protections permanentes sont, depuis quelques années, complétées par l'injection systématique de produits hydrophobes de protection temporaire, cela a contribué à diminuer les cas de corrosion en particulier sur les aubes de turbine. Il est à noter cependant que les produits de protection temporaire sont difficilement éliminés par lavage et que, sur certains moteurs, leur accumulation progressive peut modifier l'écoulement de la veine gazeuse au contact des pièces tournantes. La protection temporaire ne peut donc être considérée comme un moyen de résoudre les problèmes de corrosion sur n'importe quel moteur.

3.2. Pales d'hélices

De nombreuses pales d'hélices en alliage 2024, à l'état T3, ont présenté des corrosions feuilletantes se développant surtout à partir d'impacts sur les faces. Les problèmes de traitement métallurgique et de protection rencontrés sur les éléments de structure sont aggravés par l'érosion rapide des protections au bord d'attaque ; la meilleure protection a été obtenue au moyen de bandes collées en élastomère de polyuréthanne, néanmoins les bandes n'ont qu'une durée limitée, très variable avec les conditions d'utilisation, et elles doivent faire l'objet d'un entretien en service.

3.3. Pales d'hélicoptères

Pour les pales d'hélicoptère, la résistance à l'érosion reste le problème principal, les corrosions ont été peu nombreuses et se sont produites surtout à la limite des protecteurs de bord d'attaque en acier inoxydable. Il y a lieu de remarquer que les nids d'abeilles en alliage 5052, employés dans de nombreuses pales, n'ont pas présenté de corrosion appréciable même lorsque les hélicoptères sont utilisés en climat humide.

3.4. Equipements

Les risques de corrosion des équipements varient beaucoup : les matériaux utilisés et les conditions de fonctionnement présentent une grande diversité. Pour un même équipement, il a été parfois constaté des différences de tenue à la corrosion selon son emplacement sur l'avion, les équipements situés dans les soutes sont touchés les premiers par la corrosion comme le sont aussi les éléments structuraux situés dans les mêmes zones.

En principe, les métaux utilisés dans les équipements sont soumis aux mêmes règles générales de protections que les structures ; en fait, les servitudes de fonctionnement rendent souvent impossible la réalisation de protections correctes. Certains équipements sont placés à l'intérieur de boîtiers dont l'étanchéité est insuffisante ou le drainage mal conçu, il en résulte une accumulation d'eau de condensation génératrice de corrosion. Les corrosions les plus fréquentes sont celles de pièces en acier, visserie en particulier, qui sont seulement cadmiées. Quelques cas spectaculaires de corrosion feuilletante ont été constatés sur des éléments en alliage 2024/T3 qui avaient été revêtus de cuivre et d'étain pour assurer une continuité électrique. Dans d'autres cas, pour obtenir une bonne résistance au frottement, l'alliage 2024 avait été revêtu d'un dépôt de nickel chimique, qui a provoqué également des corrosions feuilletantes.

4. CONCLUSION

L'analyse des cas de corrosion rencontrés en utilisation montre qu'ils résultent souvent d'erreurs dans la conception des structures et de défectuosités dans la réalisation des protections.

Au stade de la conception, les causes principales d'erreur sont :
- l'insuffisance des connaissances sur la corrodabilité des matériaux ;
- l'insuffisance des connaissances sur l'efficacité réelle des protections et sur leurs limites d'utilisation ;
- la méconnaissance des règles à suivre pour éviter l'infiltration des eaux de ruissellement et de condensation dans des zones non visitables.

Au fur et à mesure que l'expérience en service a mis en évidence de nouveaux problèmes de corrosion, "l'Instruction sur la protection des aérodynes" a été remaniée pour souligner les risques de corrosion et accroître les exigences relatives à la protection. Dans son état actuel, elle prescrit d'une manière générale :
- la double protection par traitement électrochimique (ou chimique) et peinture pour tous les aérodynes, quelle que soit leur destination ;
- le montage des éléments de fixation en interposant un mastic anticorrosion.

Il est prévu, en outre, d'appliquer une protection renforcée dans les zones où les risques de corrosion sont les plus importants.

Pour chaque aérodyne un plan de protection est établi suivant ces principes, il précise les protections et les isolements anti-corrosion à appliquer pour chacun des matériaux et des assemblages ; il peut aussi tenir compte des connaissances les plus récentes en matière de corrosion et des problèmes particuliers posés par de nouveaux types de structure.

Au stade de la fabrication, les causes de défectuosités des protections peuvent être nombreuses, les plus fréquentes sont :
- l'établissement d'instructions de fabrication ne tenant pas compte de toutes les exigences du plan de protection ;
- la réalisation incorrecte des traitements métallurgiques et des traitements de surface appliqués aux pièces élémentaires ;
- l'insuffisance de qualité des films de peinture soit par suite de livraisons défectueuses, soit à cause d'une mauvaise application ;
- l'absence d'interposition au montage des assemblages et la réalisation défectueuse de l'étanchéité.

L'élimination de ces causes de défectuosité constitue le problème le plus difficile à résoudre, elle implique la certitude de l'efficacité du contrôle à tous les stades de la fabrication et chez tous les sous-traitants. Bien que des progrès aient été faits dans le domaine des techniques et moyens de contrôle, il est à craindre que la protection ne soit jamais parfaite ; les utilisateurs devront tenir compte de ce risque et continuer à prendre des mesures préventives contre la corrosion.

Les documents relatifs à l'entretien des aérodynes militaires ont subi une évolution semblable à celle de la norme AIR 7521, en tenant compte de l'expérience en service . Il existe un règlement à caractère général intitulé " Prévention et traitement des matériels techniques contre la corrosion" ainsi que des notices d'entretien propres à chaque matériel. Le règlement général a pour but d'attirer l'attention des personnels exécutant les opérations d'entretien sur les diverses formes de corrosion ainsi que sur les moyens de les éviter. La réparation des protections permanentes endommagées nécessite parfois des moyens que n'ont pas les utilisateurs mais l'application de protections temporaires hydrophobes permet souvent de protéger les éléments touchés jusqu'à ce que la réparation définitive puisse être faite. Ces produits permettent aussi de compléter les protections permanentes dans les zones recevant des condensations et d'empêcher l'humidité de pénétrer autour des fixations.

Les utilisateurs militaires français demandent maintenant que les aérodynes atteignent une durée de vie de l'ordre de 30 ans sans remplacement de pièces vitales. L'évolution des connaissances et des techniques permet d'espérer que, dans le domaine de la corrosion, cet objectif pourra être atteint, il faudra cependant que connaissances et techniques soient correctement utilisées. La formation de personnels conscients des problèmes de corrosion est donc plus que jamais nécessaire à tous les niveaux de la conception, de la fabrication et de l'entretien des aérodynes.

RECORDER'S REPORT – SESSION I

by

A.J.A.Mom
National Aerospace Laboratory (NLR)
P.O.Box 153
8300 AD Emmeloord
The Netherlands

In making a summary of the various papers given at the Monday afternoon session I would first like to give a short impression of the contents of the various papers. S/Ldr. Pye of the Royal Air Force gave an overview of the RAF policy on corrosion detection and prevention. The primary aims are keeping the life cycle costs to a minimum and trying to reach maximum aircraft availability.

The aims are achieved by an optimum corrosion prevention programme because, as the author states, "in the long term it is cheaper to prevent corrosion rather than to allow it to occur". This prevention programme is based on, among other things, paints and protective treatments, the formation of corrosion control teams, first aid kits, aircraft washing and result monitoring.

If the corrosion prevention programme does not work then a second programme comes into operation: that is the corrosion rectification programme. Also in this case rectification is considered cheaper than replacing the component in a later stage. Rectification means an effective reprotection programme during which the original paint finish is restored, and additionally other measures are taken e.g. use of water displacing fluids to prevent the reoccurrence in a short time.

Mr Browne of the U.S. Navy listed the most severe problems which were encountered in U.S. Navy Aircraft. Most problems could be traced back to water intrusion of electronic equipment and the aircraft structure itself. This led to excessive aircraft non-availability and costly repair. The problem was largely overcome due to a large joint effort between operating and maintenance people, material laboratories, manufacturers, etc. An effective sealing system was developed for the electronic connectors. Water intrusion has been diminished by the incorporation of drain holes at the right locations and effective drain hole sizes. The author states that only an active corrosion prevention programme with all disciplines involved can minimize corrosion damage.

Mr Mitchell, British Airways, expressed his concern about the fact that although the corrosion phenomena in aircraft are very well understood by both the manufacturers as well as the user the costs of corrosion are still appallingly high. A further comment was that there seems to be no fundamental change in present corrosion protection with respect to earlier aircraft manufactured 20 years ago: this is, to say the least, very disappointing. The direct aircraft maintenance costs due to corrosion are estimated to be 6–8% and this even excludes the non-availability of the aircraft.

The author spoke about the design requirements for new aircraft which have recently been changed. The manufacturer has to assess the effects of corrosion on the damage tolerance of the structure. He also mentioned the IATA document "Guidance Material on Design and Maintenance of Aircraft Structures" which gives a review of the fundamental corrosion problems and specific methods to prevent the occurrence of major corrosion.

Prof. Doruk of the METU gave an overview of the various corrosion problems occurring in Turkish military aircraft. The different locations at which corrosion occurred and the type of corrosion were mentioned. The corrosion damage was attributed to the high corrosiveness in the atmosphere at the Bandirma Air Force Base, owing to the salt and high acidity content of the air, although the author himself also emphasized that the corrosion problems were not restricted to a certain type of aircraft or a specific location in the country. Some additional information on this subject was given by Mr Inalhan of the Turkish Air Force. He stated that the major causes for corrosion were design and production faults, aggravated by improper maintenance and atmospheric conditions. At the moment the corrosion problem is completely under control.

M'elle Huret, of the Service Technique des Programmes Aéronautiques, Paris, described several examples of corrosion occurring in French military aircraft in detail, e.g. honeycomb sections and metal-to-metal adhesively bonded structures. She also gave information about the various measures which were taken to diminish the problem. The author mentioned that the manufacturing specifications do not take care of all protection requirements. Furthermore the paint systems which are applied are not the best available, or they have been applied in the wrong way. Bad sealing also occurs frequently. Other preventive measures, e.g. water displacing fluids, can given additional, short term, protection.

Apart from these short summaries of the papers, I wish to give an idea about the common themes contained in the various papers and I also wish to come back on some of the comments which were made by the audience.

I am aware of the possibility of again emphasizing the obvious, but it cannot be said often enough: the only way in which corrosion can be effectively combatted is by prevention. It was said that if the onset of corrosion occurs the operator is fighting a losing battle, and this is unfortunately totally correct. The authors agree strongly on the point of prevention and this can best be done in the design stage. In fact, three areas have to be considered: (1) the construction, notably the prevention of water intrusion and entrapment and the ease of inspection of certain areas; (2) the materials, use of more corrosion resistant materials which are often very well known is an absolute necessity; (3) the protection scheme, which means that the aircraft is protected overall in the best possible way based on the knowledge available at the time. The protection scheme thereby makes use of pre-treatments, primers, finishes, the use of water displacing fluids and sealants, wet installation of fasteners, etc. The need for better design and manufacturing will become still more urgent because the operating time of present aircraft will increase to 20 and even to 30 years. In this respect it may be stated that maintenance in service does not compensate at all for bad design. How a better corrosion prevention policy can effectively be implemented in present design practice is still a cause for concern.

Corrosion prevention at maintenance level was another important agreement between the authors. Apart from essential elements like training and education of operational and maintenance personnel; maintenance manuals which should be easy to read; a good both-way contact between maintenance people and corrosion engineers to obtain a better insight into the problem; high motivation of people; special corrosion detection equipment, etc., there is another extra way which is perhaps very attractive and that is the formation of special corrosion control teams with a high level of expertise and experience and who can go out into the field. Some authors mentioned the existence of such teams and it is worth mentioning them again.

Another aspect of maintenance which came up was the practice of aircraft washing: does it help or not, and if it is done, how should it be done and how frequently? Perhaps the audience can give definitive answers to this question.

During one of the presentations a statement was made that no aircraft were lost due to corrosion. Some people out of the audience expressed their concern about such a statement. Often corrosion will initiate a fatigue crack and it is not always noticed afterwards that such a fatigue crack actually initiated out of a corrosion pit or another kind of corrosion defect. In this context it is clear that if corrosion would be so severe that it itself affects the structural integrity of the aircraft, it will normally be noticed before e.g. failure under service loads.

If we really could trace all failures to their very basic causes then we would perhaps be still more dedicated to our task in fighting aircraft corrosion.

DESIGN AND MAINTENANCE AGAINST CORROSION OF AIRCRAFT STRUCTURES

by

H.J. Versteegen and M.J.M. Versteeg
Engineering KLM

KLM Royal Dutch Airlines
P.O. Box 7700
1117 ZL SCHIPHOL-EAST
Netherlands

The total annual direct costs of corrosion repair by IATA Member Airlines were close to $100 million in 1976. This magnitude of the corrosion problem was sufficient to cause the IATA Technical Committee to decide something had to be done about it. They set up an airline specialist group to compile guidance material against corrosion. The result was an IATA publication in February 1979, called:

"Guidance Material on Design and Maintenance against Corrosion of Aircraft Structures".

The objectives of this document are:

1. to foster a greater understanding among manufacturers and airline managements of the magnitude of the corrosion problems and the need for measures to be taken at the design stage;
2. to persuade manufacturers to develop and apply the best available anti-corrosion design knowledge in critical areas as a basic standard.

The guidelines cover basic requirements, including material choice, design principles and manufacturing procedures. Furthermore they cover the critical areas including origin of problems, design objectives and protective requirements. They are supplemented by an appendix giving a detailed acceptable means of compliance.

The total annual direct costs of corrosion repair are enormous. IATA figured that their member-airlines were close to $100 million per year in 1976. This magnitude of the corrosion problem was sufficient to cause the IATA Technical Committee to decide something had to be done about it. An airline specialist group was set up to compile guidance material against corrosion. The origin of corrosion is well understood. The technology has developed a better basic understanding of the various phenomena, associated with corrosion. It is particularly striking that in spite of what is known and learned, we are still experiencing aircraft corrosion damage that annually is increasing in costs. The millions of dollars are spent on repairs and modifications. The indirect penalties such as delays, cancellations, unscheduled downtime are no longer to be ignored.

The quoted figure, $100 million in 1976, was undoubtedly higher if one included the indirect penalties. To put it in another way, from the direct airframe maintenance costs it was more than 6 to 8 percent, not including maintenance overhead. Most aircraft types recently produced, exhibit many of the same fundamental corrosion defects as those earlier models, produced decades ago. Custom and practise have hardly changed over the years, the environment becomes worse, the operator is fighting a losing battle in his effort to maintain an airframe in the "as received" condition.
The present aircraft types will be in service around 20 years or more. Hence a general improvement in the basic protection is essential, to maintain structural integrity with an acceptable level of operational costs. The design stage is the best opportunity where the basic protection improvements could be achieved, maintenance could only be a band aid in this respect. However, still an important one.
The IATA working group took advantage of the wide variety of their members. Their assistance as well as the cooperation of the manufacturers from all over the world with their know-how resulted in the Guidance Material on Design and Maintenance against Corrosion of Aircraft Structures (DOC GEN/2637).

The objectives of the guide are two-fold:

<u>Firstly</u> : to foster a greater understanding among the aircraft manufacturers and our own airline managements of the seriousness of - and those high maintenance costs associated with the corrosion of airframe structures.

<u>Secondly</u>: to foster the need for the appropriate measures to be taken at the design stage to minimize the total costs for the operators. The design objective should be for a 20 year operational life free from significant corrosion. The present state of art allows such an objective.

For new aircraft, the manufacturers should evaluate each design detail and assembly with respect to corrosion and environmental protection. Also damage tolerance by corrosion should be included. Implementation of a formal procedure is necessary to assure that each drawing released has an appropriate sign-off indicating that the basic corrosion protection criteria are met. Even with the best corrosion protection possible, the operator should have a corrosion control program in addition to the normal operational maintenance such as clean of spills, good housekeeping etc. Repetitive application of water displacing corrosion inhibiting organic compounds should be considered as a supplemental protection system for areas prone to severe corrosion.
The operator's role should not be considered as a part of the primary corrosion prevention system. Incorporation of anti-corrosion protection in the design stage as a basic standard will minimize, expensive manufacturing variations in detail parts, sub-assemblies and final assemblies, which might be required otherwise by the individual purchaser. Operators must accept that factory-installed corrosion protection may be reflected in initial costs per aircraft. The costs, however, are generally small compared with those we have now with corrosion repair, structural modifications, in service weight increase, unexpected downtimes etc.

The intention of the document is to provide for a minimum performance specification. It is not intended as the only means of compliance. Improvements are welcome but changes should be demonstrated to the satisfaction of the operator. The basic requirements in the document include material choice, design principles and manufacturing procedures. Critical areas are indicated including the origin of problems, design objectives and protective requirements.
In an appendix acceptable means of compliance are given. The corrosion protection requirements herein can be applied to new and derivative types of aircraft and appropriate elements can be used to future production of existing types.

Following are some examples to demonstrate what was done and what could be improved according to the document:

<u>Wing skin and front spar corrosion</u>

During routine inspection, at the left outboard wing three fastener heads were found missing on a seven-year old aircraft. Visual inspection of the area forward of the front spar revealed six corrosion spots in the wing lower skin at both left and right wing. After opening up these six places, it was found that corrosion had penetrated the skin-spar chord faying surfaces.
Therefore, the whole lower skin at the front spar was NDT-inspected with the nanoscoop (an ultrasonic method). The result was corrosion at 21 places of which, after rework, 14 appeared to be out of limit and required repair with external doublers.
During repair, a crack in the lower spar-chord of the left wing was found (fig. 1). Visual inspection of the other open areas gave another four cracks. Further inspection with Eddy Current of the horizontal flange revealed a total of 21 cracks (fig. 2 thru 4). Spar chord repair was done by moon-shaped cuts and splicing in a new chord-piece.

The cause of the corrosion problem is the design of the leading edge structure. As the leading edge cavity area is open during take-off and landing, water and moisture is collected in this area, and stays, because of the wing dihedral, in front of the "dams" in the lower skin (fig. 5). At these places starts the corrosion.
The type of corrosion attack in the lower chord is stress corrosion in combination with exfoliation. The chord is fabricated from a thick 2024T3 angle, of which the inner part [illegible] insufficient quenching rate, making it prone to the kind of corrosion mentioned above. [illegible] chord was designed such that the best material properties existed at the inboard part, causing that the outboard section comes from this inner part of the angle.
It is in our opinion the free decision of the designer to make such a choice. But as the consequence is the creation of a corrosion prone material or area, he should choose the best corrosion protection system available. Figure 6 shows what has been chosen in this case, while figure 7 shows what the IATA guide describes as a minimum. The most important difference is in our opinion the omission of faying surface sealant between lower chord and skin.

This was not the only case in the fleet. Several more have been, and still are, found. Taking into account the total costs, in the order of 2 million dollars, we feel the extras required in the design have been more than justified.

Corrosion in the fuselage below the cabin floor

Severe corrosion is found in the fuselage below the cabin floor, mainly underneath lavatories and galleys, and in the cargo compartments. Some examples:
On aircraft (as young as six years) where lavatories are placed above the lower section of the aft pressure dome bulkhead (fig.8), corrosion is found in the bulkhead web, due to leakage of toilet fluids. One of the most severe corrosion ever found in this area was with the corrosion completely penetrated through the web, approximate at floor level. Reason, the design is such that toilet fluid leakage can accumulate in this area, which is not visible nor good to clean. The lower section was replaced, taking some four weeks to accomplish. The parts in this area are not anodized, only primed, and assembled without faying surface sealant.
In the cargo compartments corrosion is found due to inadequate drainage and cargo spillages. Figure 9 is an example of the latter. Corrosion has completely penetrated through the doubler, and has to be repaired with an external doubler.
It is correct to expect from an operator to clean up timely spillages, but easy access and good flush capabilities are required, and application of faying surface sealants, to prevent penetration of the moisture between these faying surfaces. While it should be obvious that this sealant is also required between dissimilar metals.
In general, the corrosion behaviour of the fuselage structure below the cabin floor can be improved by application of:

- aged-stabilized condition of forgings and extrusions made from materials like 7075;
- anodizing of aluminum details;
- primer plus topcoat on all parts before assembly;
- faying surface sealants;
- wet installation of fasteners,

and as extra, but not considered primary, prevention system water displacing corrosion inhibiting organic compounds (like LPS-3).

Pylon corrosion

On aircraft having logged approximately 6,000 flight hours, corrosion is found on the upper and lower surface of the pylon firewall and on the engine aft mount fitting. Both parts are from a low alloy steel. The pylon skin panels and stiffeners are from titanium.
The corrosion is attributed to high temperatures combined with accumulated moisture, which caused the protective coating to break down.
In addition, due to hydraulic line leaks, hydraulic fluids accumulated on the upper surface of the firewall in the area forward of the engine aft mount bulkhead. The high temperatures experienced by the structure in this area during normal flight operations resulted in the decomposition of hydraulic fluid. This caused corrosion and etching of the steel firewall and hydrogen embrittlement of the titanium structure.
To solve these in-service problems, the following modification has to be accomplished:

- Installation of blankets to reduce the temperatures on the firewall.
- Improvement of the drainage of the accumulated fluids.
- Flame spraying of the firewall with an aluminum metallized protective coating.
- Replacing the low alloy steel engine aft mount fitting with a stainless steel fitting.

The costs of the modification are in the order of $100,000 per aircraft, and the aircraft weight increase is 15 kg. The out of service time for the modification is approximately 14 days.
The selection of a corrosion resistant steel in this area (plus adequate drainage) might have increased the weight with the same amount, but would have caused less problems.

Conclusions

1. The most economic place for incorporation of anti-corrosion protection is in the design stage.
2. Each manufacturer should implement some formal procedures to assure that each drawing released has an appropriate sign-off indicating that the basic corrosion protection criteria are met.
3. The intention of the IATA document "Guidance Material on Design and Maintenance against Corrosion of Aircraft Structures" is only to provide a minimum performance specification. Improvements are welcome, but any changes should be able to be demonstrated to the satisfaction of the operator.

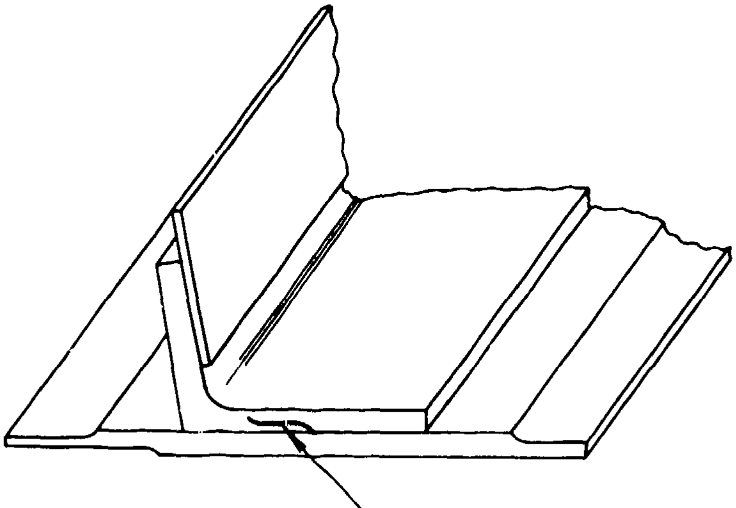

FIGURE 1: TYPICAL CRACK IN WING FRONT SPAR LOWER CHORD

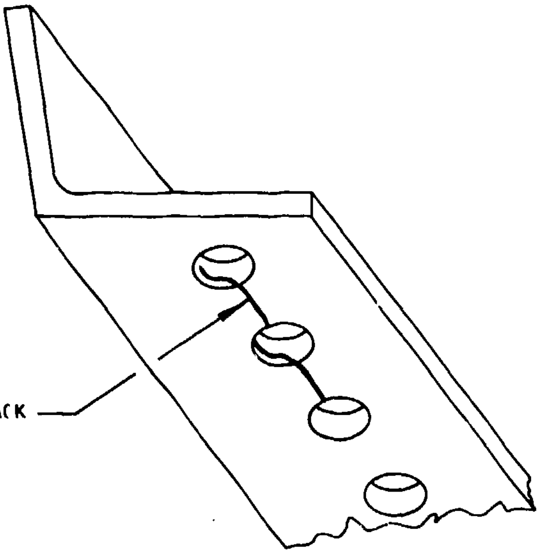

FIGURE 2: FRONT SPAR LOWER CHORD FASTENER ROW CRACKING

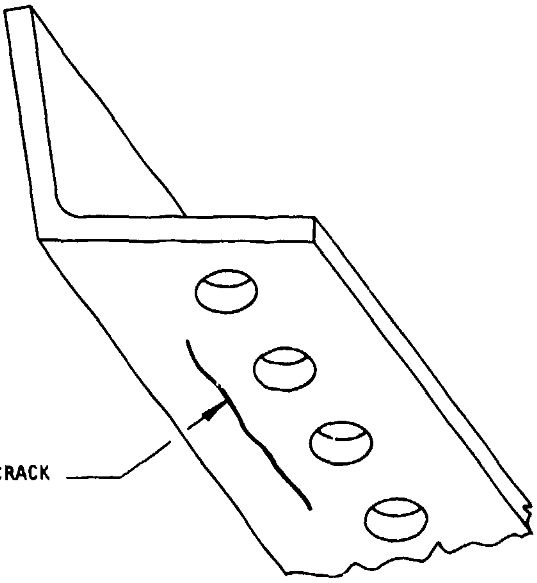

FIGURE 3: FRONT SPAR LOWER CHORD FLANGE CRACKING

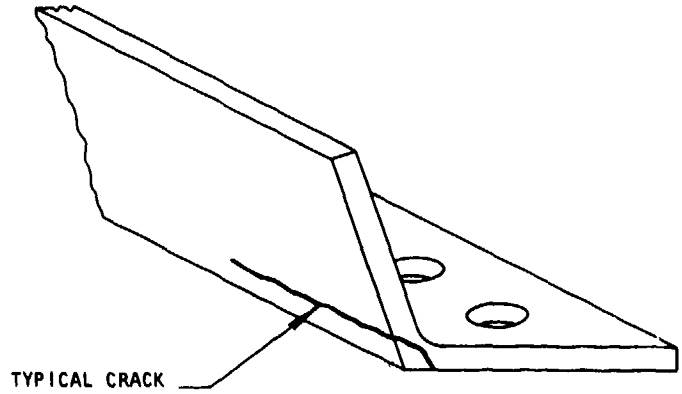

FIGURE 4: FRONT SPAR LOWER CHORD HEEL CRACKING

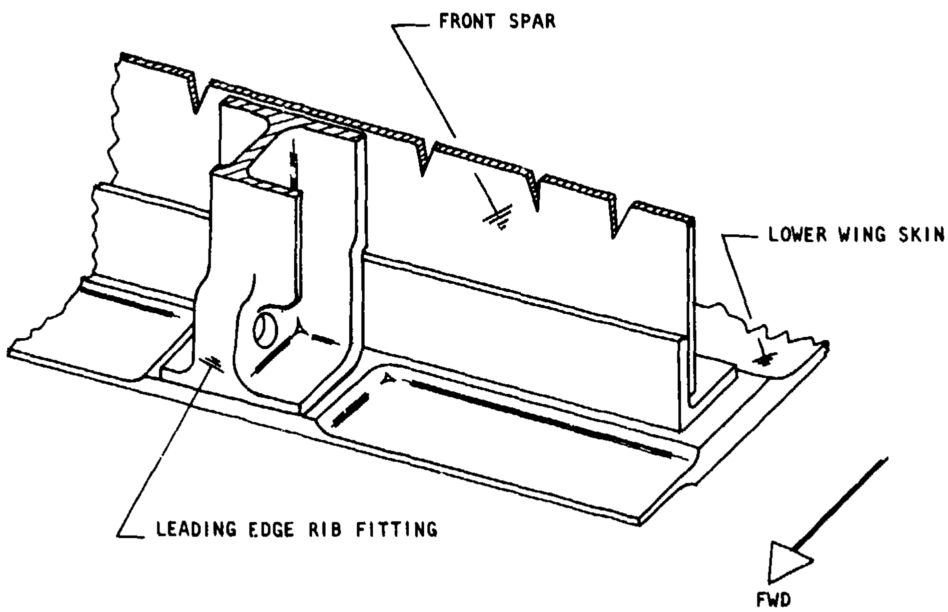

FIGURE 5: TYPICAL WING FRONT SPAR INSTALLATION

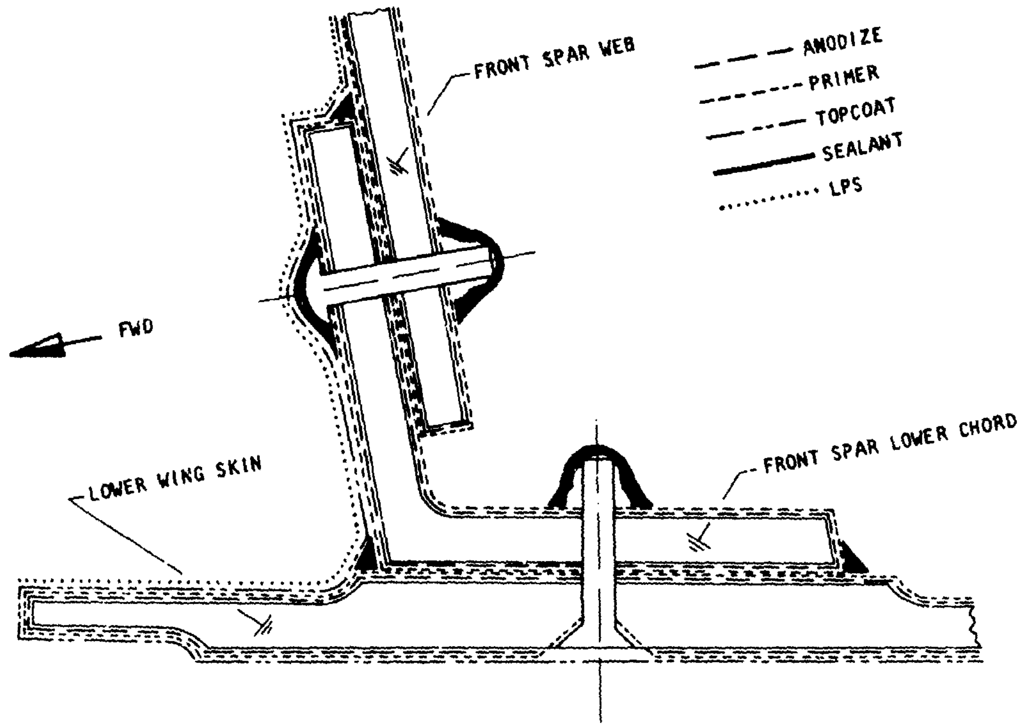

FIGURE 6: CORROSION PROTECTION SYSTEM
OF ORIGINAL DESIGN

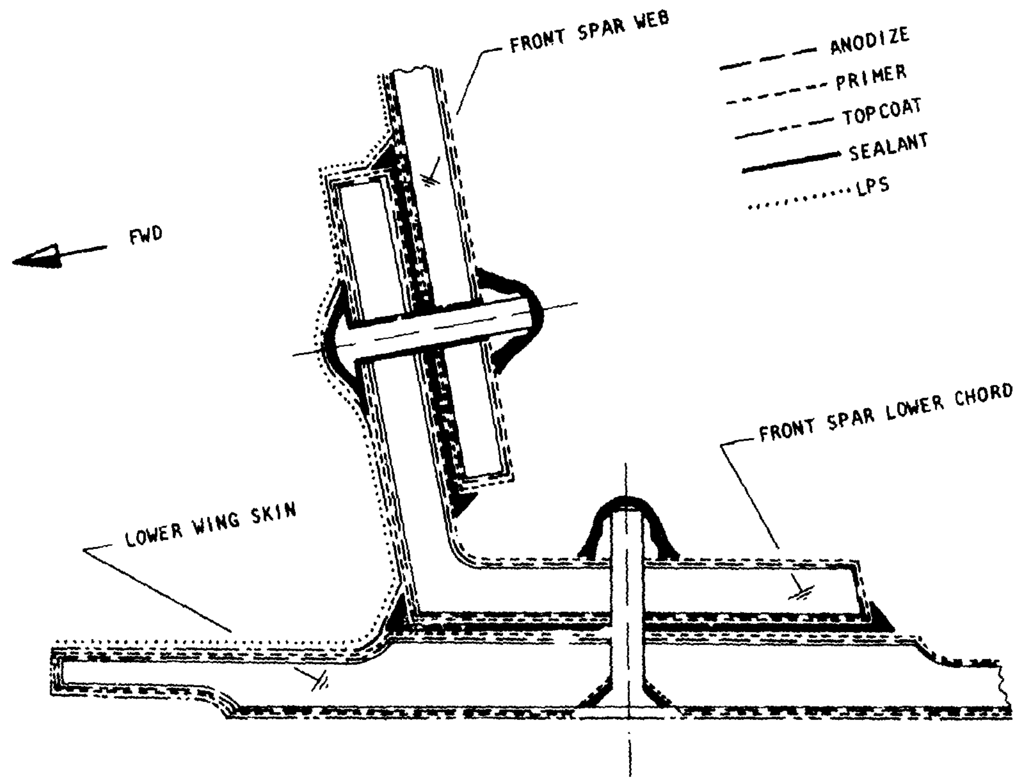

FIGURE 7: CORROSION PROTECTION SYSTEM
AS REQUIRED IN IATA GUIDE

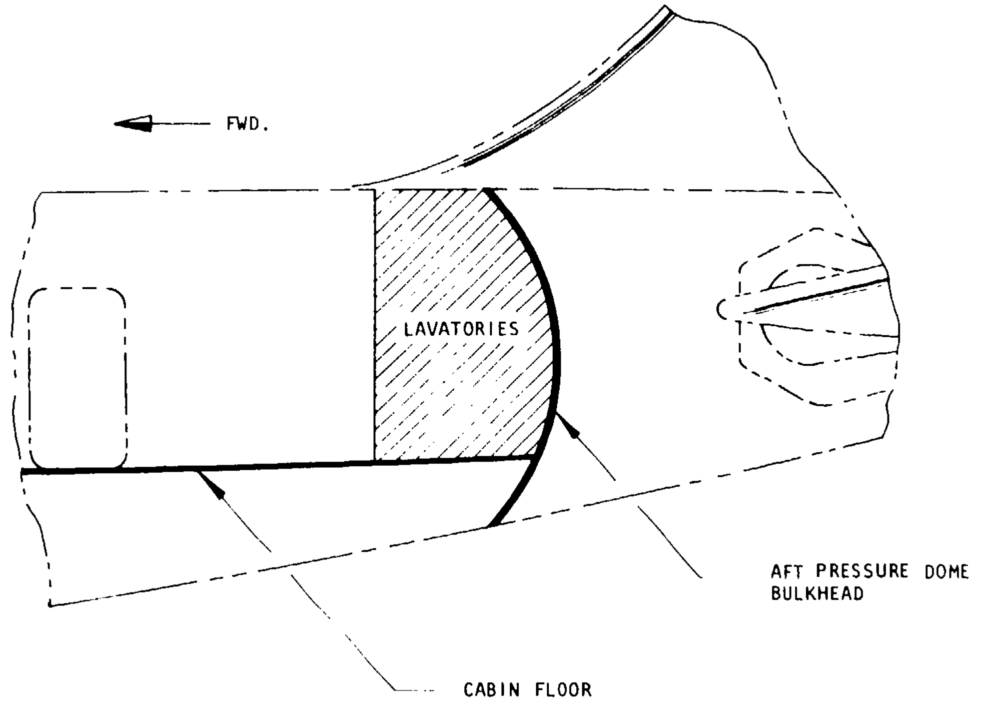

FIGURE 8: GENERAL VIEW OF LAVATORIES INSTALLATION
AT FUSELAGE AFT PRESSURE DOME BULKHEAD

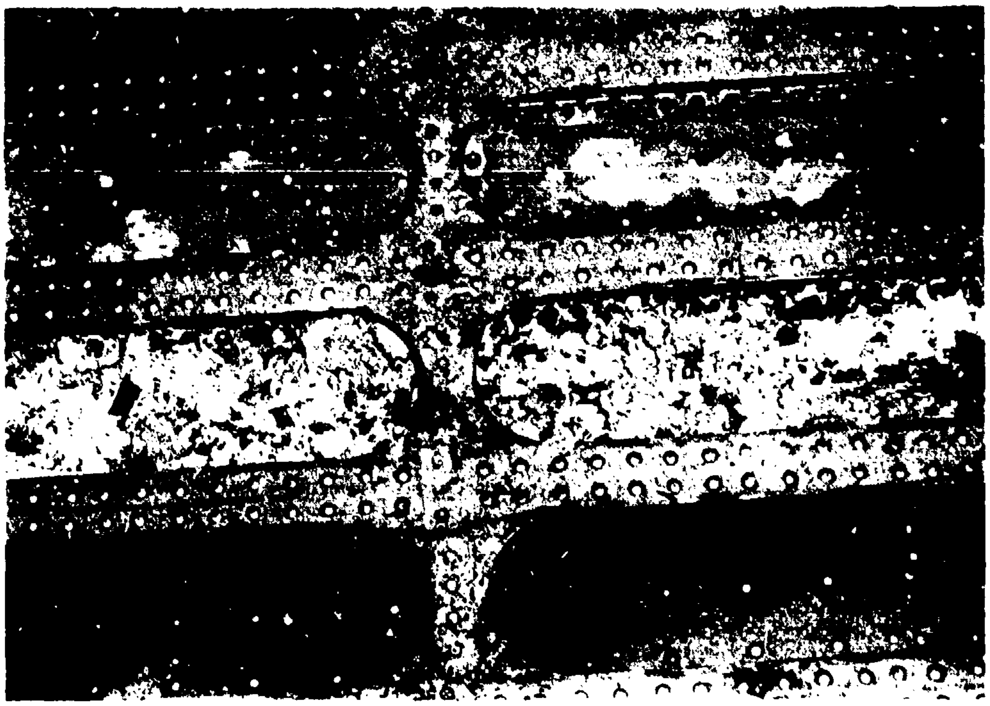

FIGURE 9: CORROSION IN THE FUSELAGE BOTTOM DUE TO CARGO SPILLAGES

FORECASTING CORROSION DAMAGE AND MAINTENANCE COSTS FOR LARGE AIRCRAFT

R. Summitt, Professor and F. Fink, Assistant Professor
Department of Metallurgy, Mechanics, and Materials Science
MICHIGAN STATE UNIVERSITY
East Lansing, Michigan USA 48824

SUMMARY

Several USAF-sponsored studies relate environmental and operational factors of large aircraft to corrosion damage, and hence provide a basis for predicting maintenance costs and for logistics decisions. These studies include: (1) An environmental corrosion severity index, based on weather and pollutant factors, (2) an atmospheric testing program to determine environmental corrosiveness; (3) Analysis of corrosion maintenance experience in aircraft systems. These programs are discussed.

1. INTRODUCTION

Efficient maintenance scheduling must be based on known relationships between damage and the exposure to risk in an operational environment. Such damage/risk relationships are reasonably well understood for consumable items and structural fatigue. Our understanding of how "environment" affects corrosion damage, however, is primitive by comparison. Several studies sponsored by the US Air Force are aimed at defining such a relation: the PACER LIME Corrosion Severity Index; the PACER LIME Atmospheric Testing Program; and analyses of maintenance histories of the C-141A and B-52D, G, and H aircraft systems; the latter is currently in progress. The PACER LIME studies actually are two phases of the same program. In the first phase a system was developed for rating environmental corrosion severity in terms of ambient parameters, e.g., humidity and pollutants. The second phase was an experimental test to measure the corrosion severity of airbase environments. Analysis of maintenance histories amounts to field or service tests of aircraft which may be used to determine environmental corrosivity.

"Environment" comprises a variety of factors relevant to corrosion. Obviously weather and atmospheric pollutants are included, but there are many others. Operational factors and the variety of environments can affect corrosion damage. Military aircraft are flown relatively little, however, hence the most important factor will be the home airbase environment. Environment also includes the quality of maintenance, which is influenced by attitude, training, and morale of personnel, as well as their numbers and extent of facilities available. Command policies of scheduling, downtime allowed, and related factors reflect the management view of the corrosion problem as well as operational requirements.

2. PACER LIME PROGRAM

AF Logistics Command developed PACER LIME to assign a corrosion severity classification to each operational airbase. There are two parts: (1) an algorithm for computing an _a priori_ corrosion index from weather and other ambient factors; (2) experimental measurement of corrosion severity from atmospheric tests. An initial corrosion factor equation was developed in 1971 and interim airbase classifications were computed for comparison with maintenance experience and the experimental results. A modified equation then would be used to compute operational corrosion severity classifications. Experimental test sites were selected to span environments from mildest to most severe, and alloys tested were representative of modern airframe construction. Despite numerous problems, considerable weight-loss data were collected. In 1978 it was determined that adequate in-house USAF resources could not be made available to complete this program. It then was assigned under contract to Michigan State University, who analyzed the test data, the Interim Classification system, and developed an improved Environmental Rating System.

2.1. ENVIRONMENTAL RATINGS

It is well established that corrosion varies widely from one location to another and environments usually are classed rural, urban, industrial, marine, or an appropriate combination (1,2) to reflect their severity. It has been shown, moreover (3,4,5), that certain factors (e.g., moisture, salt, and pollutants) accelerate corrosion rates. An environmental rating system which takes account of these factors in detail could provide a better indication of relative corrosion severity. No rating system can predict corrosion damage in general, because various metals exhibit different corrosion behavior in a given environment. The combination of corrosion factors is unique to each environment, and precise information relating the corrodibility of a specific alloy to every corrosive agent is not available. Aircraft, however, are built from only a few alloys, and, moreover, an absolute rating scale is not needed for logistic decisions; a relative rating will do. A rating system must be based on known corrosive factors which are both measureable and monitored. It is of little use to consider the corrosiveness of chemical substances for which ambient data are not available.

2.2. AIRCRAFT CORROSION AND ENVIRONMENT

Aircraft corrosion problems are of three kinds:
(1) Wet and moist corrosion of unprotected metal;
(2) wet and moist corrosion of protected metal subsequent to protective coatings failure. Protective coatings fail because of solar radiation, contaminants (mainly oxidants), ablation, and mechanical abrasion and flexure;
(3) corrosion caused by human contaminants, e.g., spilled beverages, human waste, hydraulic fluids, and battery acids.

The first and second corrosion categories can be related to the ambient environment, hence a rating system is relevant. The third, however, is a housekeeping problem.

Corrosion rates are influenced by:
(1) Weather conditions, especially those relating to moisture;
(2) atmospheric pollutants;
(3) the nature of the metal.
Moisture will deposit from humid air on metal via condensation, if the metal is colder than the air; via absorption, if hygroscopic salts are present; or via chemisorption (6). The amount depends on humidity and the adsorption process. Dew, fog, and rain, on the other hand, wet surfaces at once. Although dew condenses when air cools to its dew point, the air itself need not cool to this temperature before moisture accumulates. It is necessary only that the metal be cold enough to chill adjacent air to the dew point (6).

Much discussion has centered on the effects of rainfall (4). Rain provides moisture for corrosion, but also washes away corrosion products and pollutant deposits. Thus light rain would be harmful, but heavy, washing rain would be beneficial. The beneficial effects are unimportant in aircraft because, generally, paint protects surfaces exposed to rain, and corrosion occurs beneath the paint. Moreover, interior surfaces carelessly exposed to rain are wetted and not washed.

Temperature, humidity, sunlight, cloud cover, and wind influence water evaporation, and temperature also influences corrosion rates; it is difficult, however, to predict the effect of these variables on corrosion rates (3).

Atmospheric pollutants known to accelerate corrosion or materials degradation are (7):

(1) Particulates, including sea salt, land dusts, combustion soots, and agricultural and industrial dusts. Unfortunately, composition data are sparse, yet the corrosiveness of particulates varies widely. In the case of salt, however, corrosivity is well established; for other particulates, there exist few studies which show corrosion is more severe in air containing them, and these studies are ambiguous because other corrosive factors were present.

(2) Gaseous pollutants including sulfur dioxide, nitrogen dioxide, and photochemical oxidants. Although other gaseous substances are corrosive, few are both widespread and monitored.

These factors vary from one location to another. Environmental corrosivity becomes increasingly severe as the severity of these factors increases, but, at low values, their effects on corrosion are negligible (3). It is reasonable to assume that a threshold value exists for each factor which may sharply separate slow and rapid corrosion, or the rate of damage may vary gradually with the factor. Where such threshold values are known, they can be used as environmental severity standards. Unfortunately, except in the case of humidity, such data do not exist. The problem is to determine the level at which each of these factors, and hence, the environment becomes corrosive.

2.3. ENVIRONMENTAL CORROSION THRESHOLDS (ECT)

Environmental corrosion thresholds might be developed from the following:

(1) The range of values for ambient parameters establishes limits of environmental exposure, if not the damage to be expected. Since real environments are known to vary in corrosion severity, it follows that practical threshold concentrations must be within this range.

(2) Ambient air quality standards, established by the US Environmental Protection Agency (8,9), are based on available evidence for maximum levels safe for human health. Materials may endure higher concentrations without apparent ill effects, or may suffer damage from long-term exposure to lower concentrations; nevertheless, these values are a "bench-mark" for damage to something.

(3) Experimental studies relating damage to pollutants and weather may provide information for establishing ECT; several, using both real and simulated environments, have been published (10-15).

2.3.1. THE RANGE OF AMBIENT PARAMETERS

Weather data are collected by several agencies (e.g., Reference 16) and commonly are measured at airports because weather is critical to flight safety. Air quality data are collected in the US by federal, state, municipal, and private agencies, and are compiled by states and the US Environmental Protection Agency (17, 18) to evaluate air quality in more densely populated regions. The results represent population distribution, rather than geography, and may not represent environments to which aircraft are exposed. Moreover, many monitoring stations track specific pollution sources, hence reflect localized conditions. Nevertheless, the EPA data are the best source to assess the range of exposure.

Graedel and Schwartz (19) analyzed US atmospheric conditions and reported a 50-th percentile median (an "average of means"), and a 99-th percentile median, the level exceeded at 1% of monitoring sites. Graedel and Schwartz termed the 99-th percentile medians as Atmospheric Upper Limit Values (AULV), i.e., one percent or less of environments will have levels higher than these. Threshold levels probably lie between the median values and the AULV's.

Accelerated corrosion near the seashore is correlated with airborne salt, but establishing a critical distance from the shore is difficult because there is little data relating either corrosion to salt concentrations, or airborne salt to distance from the shore. Large salt particles settle rapidly, but small particles persist in the air far overland and provide condensation points for rainwater. Chloride in rainwater over landmasses is correlated with small particles, whereas direct settling of large particles occurs near the shore. The decrease of chloride in rainwater occurs slowly over large distances (20,21), but the decrease in corrosion damage is quite abrupt (22,23). Hence rainwater chloride does not appear relevant. Literature evidence (20,24-26), together with limited corrosion data (22,23) suggest that particulate salt concentrations and corrosion rates both decrease to about 4 km, most of the decrease occuring within 1.5 km from shore; both corrosion rates and salt concentrations appear to be constant beyond 10 km.

2.3.2. AIR QUALITY STANDARDS

The US Federal Clean Air Act (8) directed the Environmental Protection Agency to promulgate national ambient air quality "standards" (primary and secondary) based upon air quality "criteria." Primary standards were to protect public health, whereas secondary standards were to protect public welfare, presumably including materials. "Air Quality Criteria" (27-31) summarize the scientific knowledge relating pollutant concentrations and their effects to assist the development of standards. "Criteria," which pertain to effects observed when the ambient level of a pollutant has reached or exceeded a specific value for a specific time interval, mainly concern effects of pollutants on human, animal, and plant health. Studies related to materials are meager, and often seriously defective. The "National Ambient Air Quality Standards" have but a tenuous relation to corrosion, and are of little relevance to aircraft problems.

2.3.3. EXPERIMENTAL STUDIES

The paucity of information relating corrosion to pollutants results from the infancy of the field. Although some progress has been made (4-6,10-15) there is no experimental basis for determining at what concentration a pollutant becomes harmful to metals, hence no guidelines for setting threshold values can be justified. It is known only that metallic corrosion is accelerated by nitrogen dioxide, oxidants, and other particulates. Protective finishes deteriorate in the presence of solar radiation, oxidants, some particulates, and possibly nitrogen oxides and sulfur oxides. Published research does not tell us, however, at what level these factors become damaging (27-31).

2.3.4. PRELIMINARY CORROSION THRESHOLD VALUES

It is our view that threshold levels are within the range of ambient values, because accelerated corrosion and materials deterioration does occur in existing environments. We adopt arbitrarily two sets of Preliminary Corrosion Threshold Values (PCTV's) based, in part, on the analysis of Graedel and Schwartz (19): the first set includes their 50-th percentile values, and the second their 50-th percentile values plus 20 per cent of the difference between the 99-th and 50-th percentiles (Table 1).

Table 1. Preliminary Corrosion Threshold Values

	Annual Mean	
	I	II
Suspended Particulates, $\mu g/m^3$	61	86
Sulfur dioxide, SO_2, $\mu g/m^3$	43	72
Ozone, O_3, $\mu g/m^3$	36	47
Nitrogen dioxide, $\mu g/m^3$	64	78
Absolute humidity, AH*, g/m^3	7.1	9.0
Distance to sea or salt source, km	4.5	2
Solar radiation, July (Langleys)	600	650
Rainfall, cm total	125	150

*Absolute humidity is the product of relative humidity and the mass of water in one cubic meter of water-saturated air at a given temperature.

Threshold distances to salt or seashore are based on the above-mentioned analysis of published data relating particulate salt concentrations (24-26) and corrosion (3,22,23) to distance from the shore. Solar radiation and rainfall thresholds are the mean (July) and annual mean values, respectively, for the continental US (32).

2.4. CORROSION MAINTENANCE IN AIRCRAFT

Excluding housekeeping, corrosion maintenance involves
(1) washing exterior surfaces,
(2) repair/replacement of protective coatings, and
(3) treatment/repair of corroded components.

Environmental elements which corrode metal in general are not the same as those which deteriorate paint, hence a single-rating algorithm cannot classify an environment for all three activities. We propose three algorithms for computing environmental severity ratings by comparing locally-measured ambient conditions with the PCTV's. Each algorithm yields a severity rating after successive comparisons of each relevant factor with the appropriate PCTV. The several combinations of high or low values yield one of the possible ratings, which is a simple three- or four-step scale, e.g., A, B, or C, in decreasing order of severity; a more elaborate system is not needed. It is possible to replace yes/no decision points of these algorithms with a numerical scale related to the magnitude of each environmental factor, and the resulting rating could be the sum or another combination of the numerical factors. In our view, however, the scientific foundation at this time is not adequate for such extension.

In this paper, we discuss only the aircraft Corrosion Damage Algorithm, (CDA), which provides a guide for anticipating corrosion damage and for planning personnel and downtime required. This guide is of a general nature, as contrasted with the washing and repainting algorithms, which recommend definite time intervals for these actions (33 a). The Algorithm (Figure 1) first considers distance to salt water (or salt flats), leading either to the very severe (AA) rating or a consideration of moisture factors. After moisture factors are compared with the threshold values, pollutant concentrations are considered. A high moisture factor and a high value for any of the three pollutants leads to the severe (A) rating;** a high moisture factor with low pollutant factors leads to the moderate (B) rating. Low moisture factors and a high pollutant value also result in the moderate (B) rating, whereas if all are low, the mild rating (C) results. We have computed environmental severity ratings for all USAF, Air National Guard and Air Force Reserve airbases in the US, and for several other corrosion test sites (33 a). These ratings are compared with the results of several testing programs in the following sections.

**In the current CDA, corrosive effects of particulates and oxidants may be overemphasized, since they are weighted as equally significant as sulfur dioxide.

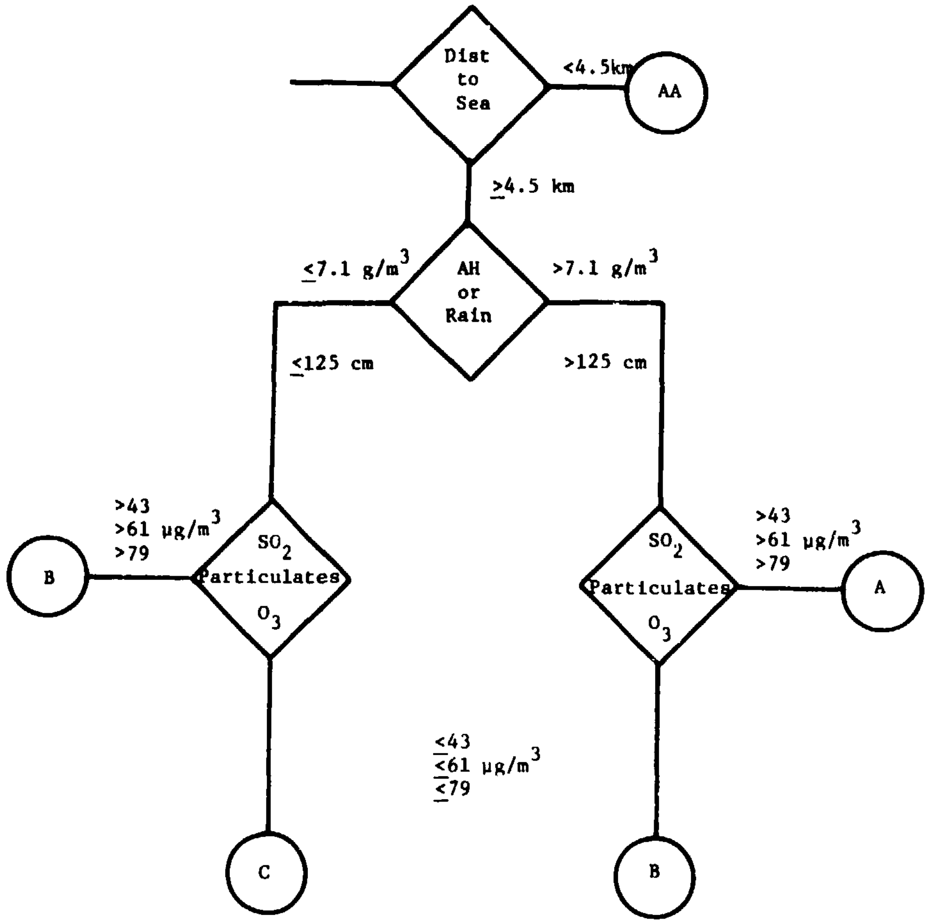

Figure 1. Corrosion Damage Algorithm for aircraft using set I of Preliminary Corrosion Threshold Values.

2.5. ATMOSPHERIC TESTING PROGRAM

Alloys tested were 2024 T3 alclad, 7075 T6, and 7079 T6 alclad aluminum; 4340 steel; AZ31B magnesium; and titanium -6Al-4V as panels 127 x 143 x 1.5 mm, 127 x 298 x 1.5 mm, and a riveted assembly of the three aluminum alloys. Panels were degreased, descaled, and weighed initially, and, at six month intervals, they were removed, descaled, and weighed. Panels were fastened by means of porcelain insulators at 30° to the horizontal, facing prevailing winds in a general airbase environment. Corrosion rates, as mass decrease per unit area per unit time, were computed by multiple linear regression analysis from the weight vs. time measurements.

This study might have yielded extensive data, but the useful information actually obtained is small. Although panels tested numbered 1089, it was necessary to combine data for each panel type at each test site, reducing potential corrosion rates to 110. Only 33 apparently valid rates, in fact, could be computed. A variety of misfortunes are to blame, including test stands destroyed by weather, loss of specimens and data, and accidents which plague all long-term experiments. The results obtained, however, and those of others for the same alloys may be compared with the Corrosion Damage Algorithm ratings for the test sites in question.*

2.6. ATMOSPHERIC CORROSION RATES COMPARED WITH CORROSION SEVERITY RATINGS

Data are sufficient from this study to make environmental comparisons only for AZ31B, 2024, and 7075 alloys. For 7079 there are but four values, but several literature values are available. Semi-quantitative comparisons with environment are shown for these four alloys in Figures 2 - 5, where experimental corrosion rates are plotted vs. the CDA rating.

*Experimental results and a more complete discussion may be found in Reference 33 b.

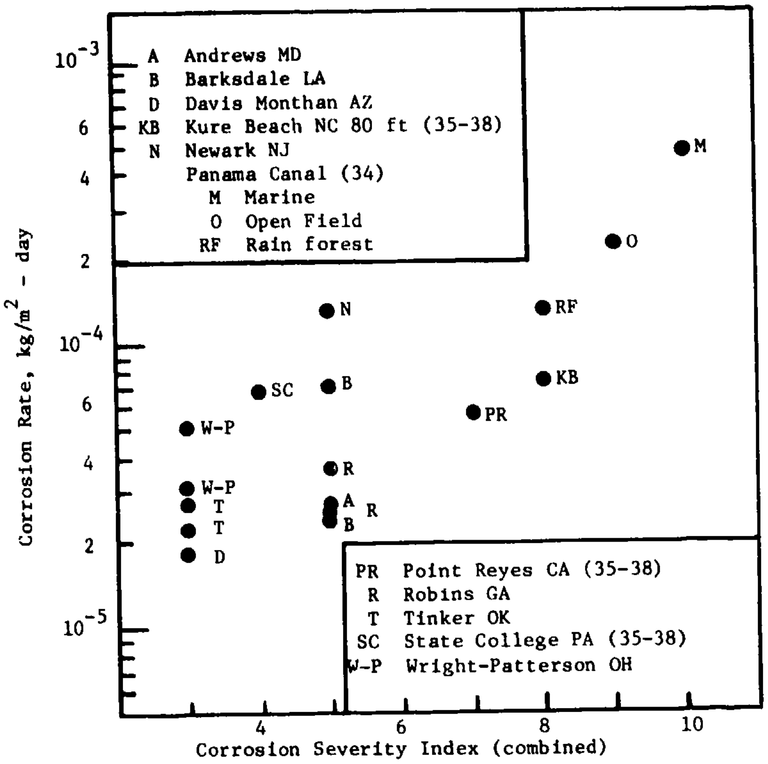

Figure 2. Corrosion Rates of AZ31B Magnesium Alloy Compared with Environmental Ratings. Caption Numbers are References.

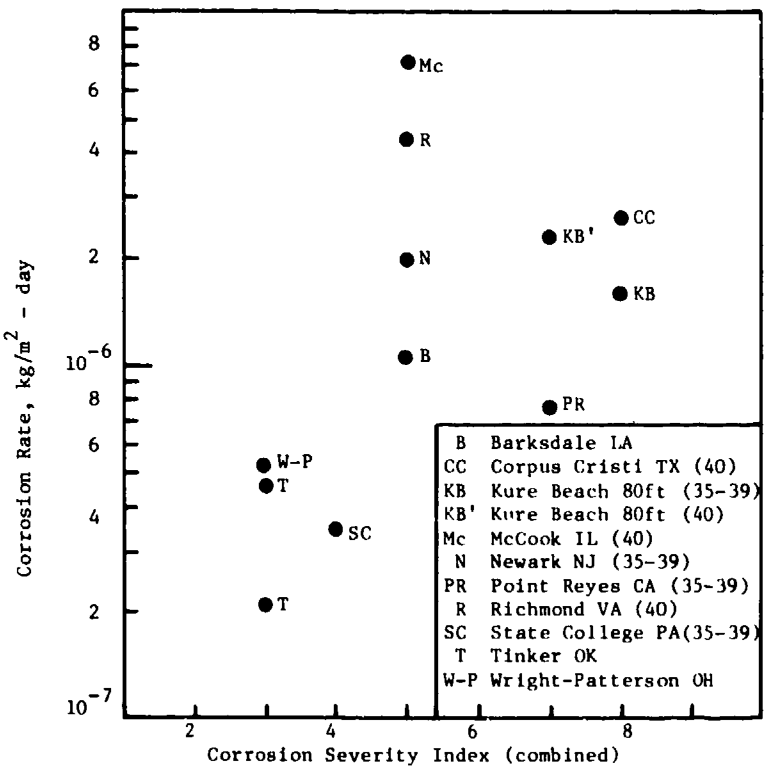

Figure 3. Corrosion Rates of 2024 T3 Alclad Aluminum Alloy Compared with Environmental Ratings. Caption numbers are references.

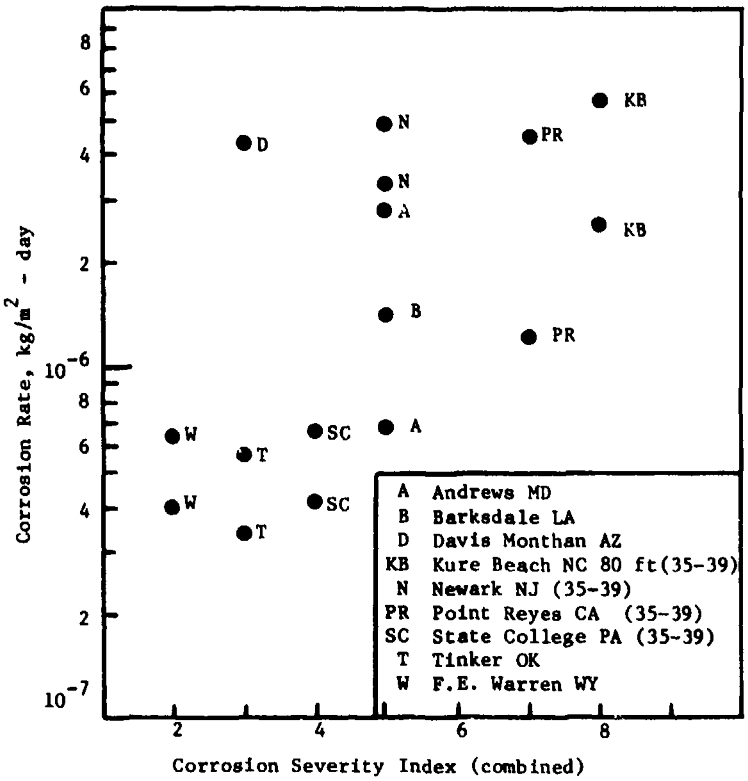

Figure 4. Corrosion Rates of 7075 T6 Aluminum Alloy Compared with Environmental Ratings. Caption Numbers are References.

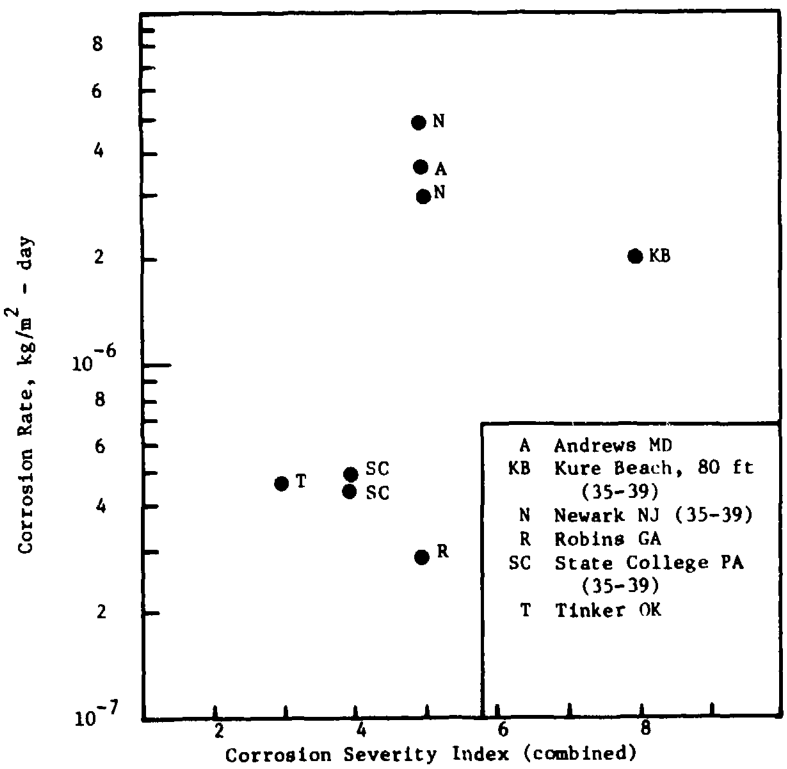

Figure 5. Corrosion Rates of 7079 T6 Alclad Aluminum Alloy Compared with Environmental Ratings. Caption Numbers are References.

The CDA provides a two-letter scale, viz. "BB," "AB," etc., the first of which is derived from the less-tolerant threshold values, and the second from the more-tolerant set of Table 1. Thus a second-letter "A" indicates a more severe environment than does a first-letter "A." Environmental CDA ratings range from the mildest "C" through "B" and "A" to the most severe "AA." For plotting data, these letters were converted to a numerical 1 to 4 scale for "C" to "AA," respectively, and the two-letter values were summed. Thus an "AB" environment yields the sum 5, and "AA,AA" yields 8.

Data for the magnesium alloy, Figure 2, show a good correlation with CDA ratings. The literature corrosion rates for State College, PA and Newark, NJ are somewhat high, but the data from this study are consistent. In the case of 2024 T3 alclad, Figure 3, nearly all the results are consistent except for literature values from two sites. The data for 7075 T6, Figure 4, are similar to those of 2024 T3. The 7079 T6 data from this study, only four points, are plotted in Figure 5 together with literature data; all are consistent with the environmental ratings.

The experimental phase of this study was expected to yield data for calibrating the interim Corrosion Factor Equation from weight-loss measurements. The results are not as useful as expected because:

(1) Metals tested were typical aircraft alloys, but not especially suitable for measuring environmental corrosivity by weight-loss methods. The aluminum alloys are relatively resistant to general corrosion, hence weight losses were small and potential experimental errors large. Similarly, the titanium alloy did not corrode and yielded no information.

(2) Test sites which yielded data have similar more-or-less "moderate" environments, whereas the "mild" and "severe" test sites selected were unproductive.

(3) An unreasonable share of misfortune.

Nevertheless, the results are in agreement with those of other workers and they correlate well with environmental ratings from the Corrosion Damage Algorithm. The data are insufficient, alone however, to calibrate an environmental rating system.

3. USAF MAINTENANCE EXPERIENCE

The established deployment of aircraft systems can provide the basis for a large field or service test which relates exposure in a "natural" environment with corrosion damage. There are three such studies of USAF aircraft, viz., the C-141A (42), the B-52D, G, and H, and the F-4 (43). The B-52 study currently is in progress and will be discussed with some results from the C-141A study.

Any corrosion test must satisfy three requirements:

(1) A damage criterion, e.g., weight loss or pit depth;

(2) a method to measure damage; and

(3) a data set, with some means to assess its reliability and to interpret results.

Several features of these aircraft studies are unlike orthodox corrosion tests, and may be discussed in terms of these requirements. These unique features result from the use of the USAF maintenance data (collected under AFM 66-1 "Maintenance Data Collection System," Ref. 44) which documents nearly all actions. The use of such data implies that the researchers have no control whatever over exposure conditions, data collection, or any other facet of the "experiment." Moreover, data are collected by personnel who are completely without experience in corrosion research -- although highly expert in corrosion repair -- viz. maintenance personnel, who represent a wide range of skills and experience.

Our criterion of damage is simply that a component has been determined to require repair during an inspection. Damage tolerance levels are established for every item inspected, but a decision that a repair is needed is based on subjective comparison with these tolerances, hence a spectrum of actual damage will be reflected in the maintenance data reports. No other damage criterion is possible, however, since without this need-for-repair decision, no damage is documented.

Two measurements of damage are provided by MDCS data: (a) Frequency of failure, as the number of maintenance actions in a given time interval; (b) cost of repair, as the number of manhours required to effect repairs. The latter, of course, is an incomplete statistic since it reflects labor costs only, and not the cost of replacement parts. At this stage, however, we seek comparisons of corrosion damage from one environment to another, not an evaluation of total corrosion costs.

Under the AFM 66-1 System, virtually every aspect of a maintenance action is documented and entered into a computer system at the maintenance facility. Periodically, facility-level data are edited and forwarded to a central computer. The reliability of this data is subject to all of the "nontraditional environmental" effects, i.e., those related to human factors rather than ambient conditions such as weather.

3.1. ANALYSIS

Complete maintenance records of the C-141A and the B-52 forces, for the time intervals 1970-1976 and 1975-1979, respectively, were made available for this study. These records were edited to select corrosion-related maintenance actions, upon which further analyses were performed. Records selected were those which contained either a failure- or repair-identifier code from a list of corrosion-type codes. There is some basis for argument that these lists exclude some corrosion-relevant data, or that items are included which are not relevant. Our analyses and research show this to be a minor factor. Moreover, our objective is to compare maintenance with environment, hence the influence of such factors will be minimal since all locations were treated in the same way.

For the purposes of environmental comparisons, the data were sorted into field-level actions and, in the case of the B-52 models, by aircraft series. Further, the data have been normalized to a per aircraft per month basis. In this paper, we discuss only the total labor corrosion maintenance costs as manhours per aircraft per month, without further breakdown. Of course, many relevant factors are omitted from such a simplified approach, but the results serve to illustrate the comparison with environment in a manner similar to that shown above for atmospheric corrosion tests. This comparison is shown in Figures 6 - 9 where the CDA ratings have been converted to a numerical scale above.

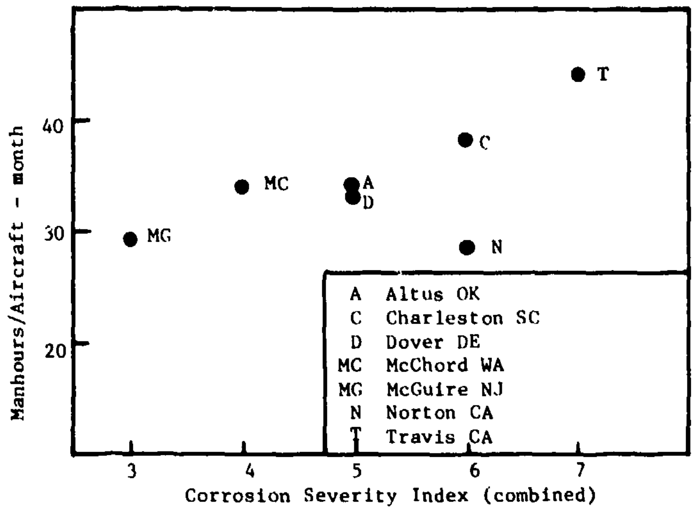

Figure 6. C-141A Corrosion Maintenance Effort Compared with Environmental Ratings.

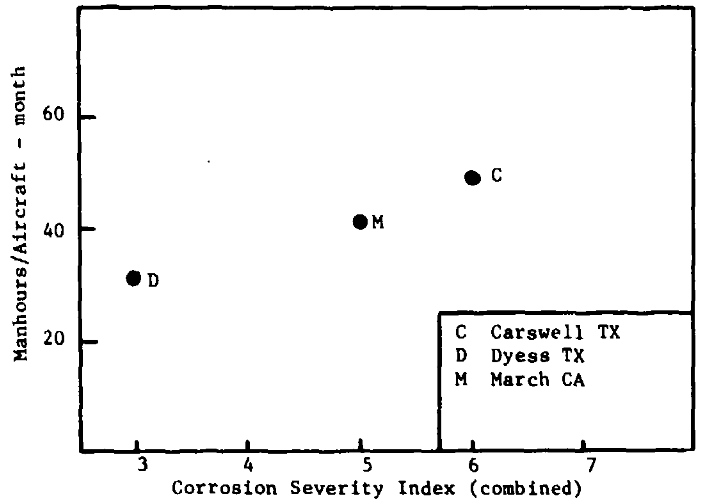

Figure 7. B-52D Corrosion Maintenance Effort Compared with Environmental Ratings.

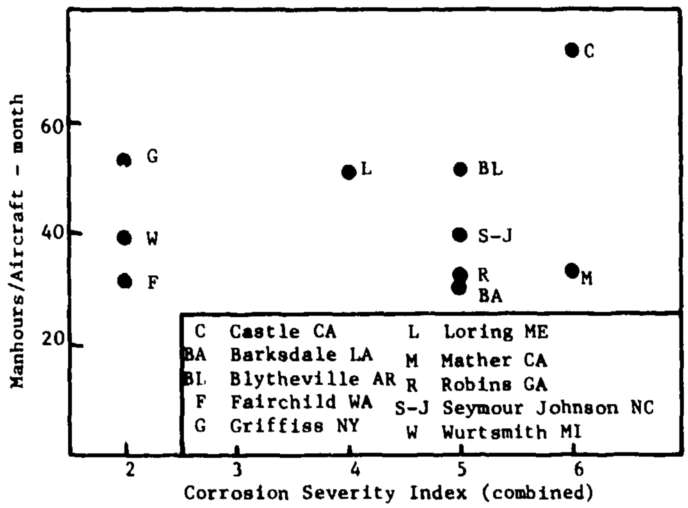

Figure 8. B-52G Corrosion Maintenance Effort Compared with Environmental Ratings.

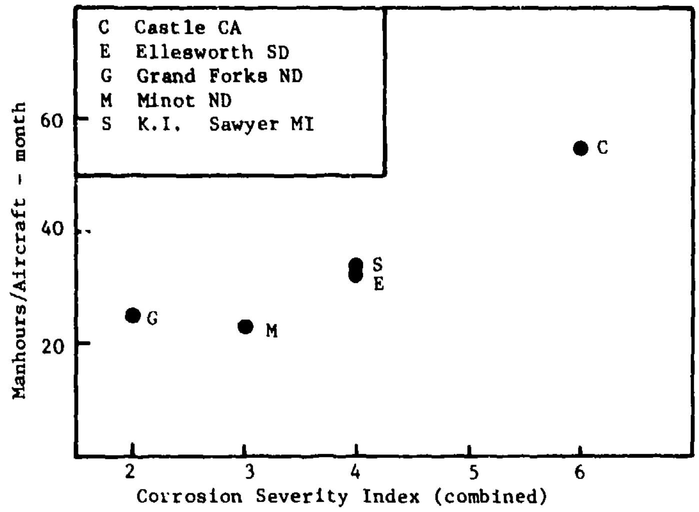

Figure 9. B-52H Corrosion Maintenance Effort Compared with Environmental Ratings.

Field maintenance data for the C-141A, B-52D, and B-52H aircraft are in good agreement with environmental ratings. The results for the B-52G aircraft, however, show a poor correlation. the reasons for which are not clear at this time. Environmental data are known to be inadequate for certain sites: for at least one site, an additional corrosive factor (acid rain) is present but was not included in the CDA rating. This latter site exhibits corrosion above the level expected on the basis of the CDA.

4. CONCLUSION

An environmental Corrosion Severity Classification System, proposed by USAF personnel in 1971, was to be used for anticipating corrosion-related damage to aircraft and hence for scheduling appropriate repairs and maintenance actions. The USAF interim classification method has been extended to the algorithm format described here. Using the algorithms, environmental severity ratings have been computed for nearly 200 sites. Ratings have been compared with actual corrosion damage measurements from: (1) an experimental atmosphere exposure test conducted as part of this program; (2) experimental atmospheric exposure test results reported in the literature; and (3) USAF corrosion maintenance experience with large aircraft. All these experimental results provide excellent support to the environmental ratings. For the purposes of relating environmental risk and military aircraft corrosion maintenance, we conclude that this system is the most advanced tool available.

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CORROSION CONTROL MEASURES FOR MILITARY AIRCRAFT - PRESENT UK REQUIREMENTS AND FUTURE DEVELOPMENTS

by

V. C. R. McLoughlin
Materials Department
Royal Aircraft Establishment,
Farnborough, Hampshire GU14 6TD, England

SUMMARY

Within "Design Requirements for (UK) Service Aircraft" (AvP970) the aircraft designer is given advice on the selection of metallic materials based on their resistance to corrosion; the designer is also presented with mandatory requirements for processes and materials used in the protection of aircraft structures. The philosophy behind this approach is discussed and the various corrosion control requirements are described. While the protective schemes currently used on aircraft structures are generally satisfactory it will probably be necessary to find replacements for cadmium (for the protection of steel), for chromates (for inhibition of corrosion, especially when incorporated in paint films), and various metal finishing operations, because of the pressure of current and future legislation aimed at protecting the environment. The impact of such legislation is discussed, together with possible solutions, based on current research work in the UK.

1 INTRODUCTION

Military aircraft manufactured in the United Kingdom are designed to the requirements of AvP970 [1] and any departure from these requirements must be agreed by the Ministry of Defence. In AvP970 the measures to be taken to ensure satisfactory resistance to corrosion and deterioration are set down. The main requirements are in chapter 801 (Precautions Against Corrosion and Deterioration), but there are other chapters which deal with corrosion and its avoidance. In this paper these various requirements are described with emphasis on the approaches taken to ensure that UK military aircraft are built to the best possible corrosion prevention standards. The philosophy is, not surprisingly, very similar to that adopted in the manufacture of civil aircraft; the relevant parts of AvP970 were drafted after taking advice from UK civil aircraft manufacturers. To achieve a satisfactory level of protection it is necessary to consider, not in isolation but in relation to each other, the detailed design of aircraft, the selection of structural materials and methods of protection. While all three aspects merit equal consideration the main emphasis in this paper will be on protection, both current techniques and future developments.

2 DESIGN

In the design of aircraft structures it is vitally important that water and other liquids cannot become trapped within the structure. The first consideration must be to seal the structure adequately so that, as far as possible, water and other liquids are prevented from entering the structure and equipment within the aircraft. In practice it is not possible to seal an aircraft structure totally, while some liquids are generated within the aircraft; for example, in galley and toilet areas, throughout the structure by condensation of water from the air, and from leakages of operating fluids. Therefore, it is essential to drain and vent, both in flight and on the ground, all parts of the aircraft except where complete sealing is achieved. Detailed design should ensure that any liquids present can flow unimpeded to drainage holes. Any pockets which are unavoidable should be filled with an adherent, inert, non-porous, lightweight material. It is essential that crevices do not exist in the finished aircraft, and the designer must accept the necessity of wet assembly to achieve this objective. This important aspect is dealt with in more detail in the section on protection.

One of the areas where corrosion frequently starts is at corners or edges of metallic components. It is a general requirement that sharp edges and corners are well rounded; this also helps in achieving a uniform application of protection schemes, and promotes good adhesion of coatings. It is also a general requirement that all parts of an aircraft structure should be accessible for inspection, apart from parts which are designed to be completely sealed. This is important in the early detection of cracks and corrosion, and also to enable rectification and reprotection to be carried out effectively.

3 SELECTION OF MATERIALS

Well established high strength alloys are often chosen by the designer because of their successful application in older designs, and sometimes despite their not-so-successful use. Using these materials is not always the best method of ensuring adequate corrosion resistance. Recently developed materials and heat treatments can achieve a far better compromise of structural strength, weight, and corrosion resistance. To encourage the designer to use alloys with inherently better corrosion resistance information is now available (or has been agreed for inclusion) in AvP970 on the relative resistance of aluminium alloys to exfoliation and stress corrosion, and of steels to stress corrosion and hydrogen embrittlement. Examples of this information are given in Tables 1 and 2. The alloys which are very susceptible to these forms of deterioration (those classified D in Tables 1 and 2) can be used only with the prior approval of the Aircraft Project Director, while those materials classified C (which are somewhat less susceptible) should only be used after taking advice from materials specialists. The aim is to give information to the designer which enables or persuades him to use materials resistant to exfoliation and stress corrosion. At the same time materials very susceptible to these forms of attack have not been banned; the designer is required to explain why he considers that they should be used and to convince the customer that their use will, overall, be beneficial. In arriving at the classifications of the various aluminium alloys and steels both laboratory evaluations and the performance of the materials in service have been considered. When, as so often happens, laboratory tests and real time experience do not agree classification is based largely on the performance of the materials in aircraft structures.

3.1 Cladding of aluminium alloys

It is worth noting that aluminium is very resistant to corrosion, but this resistance is dramatically reduced by the presence of certain alloying and impurity elements. Of the aluminium alloys used in aircraft structures those containing copper as the major alloying element are the most susceptible to corrosion. These alloys can be protected very effectively by cladding with 99.7% aluminium which contains less than 0.2% iron and 0.02% copper. The total thickness of the clad layers is between 2% and 4% of the total thickness of the fabricated sheet or plate; the higher figure is used for sheet material up to 3 mm thick. The cladding protects the alloy core not only because it is far more corrosion resistant, but also because it is anodic to the core alloy (see Fig 1). The clad layer thus acts as a sacrificial coating in the same way that cadmium or zinc coatings protect steel, even when they are scratched or otherwise damaged to expose the substrate metal. The high strength aluminium-zinc-magnesium-copper alloys are little different from the aluminium-copper alloys in corrosion resistance, and the use of a sacrificial cladding is of equal benefit. However, the corrosion potentials of aluminium and the Al-Zn-Mg-Cu alloys are very similar, and there would be no sacrificial protection of the core alloy by an aluminium cladding. A more anodic coating, such as aluminium -1% zinc, must be used (see Fig 1).

Cladding is a very useful protection for high strength aluminium alloys, but it does not come without certain disadvantages. Compared to the core alloy, a clad material will have lower strength, lower fatigue strength and will be less abrasion resistant. The reduction in strength is particularly noticeable in the case of clad plate alloy which is machined to remove substantial amounts of metal from one side, resulting in a greater proportionate thickness of cladding to core alloy. This objection can be overcome to a major extent by using a higher strength cladding[2], such as an aluminium-zinc-magnesium alloy, which is still anodic to the aluminium-zinc-magnesium-copper alloy core and makes a significant contribution to the strength of the final structure.

In the UK clad sheet alloy is generally used for fuselage structure, but plate alloy is usually unclad.

It is worth noting that the fatigue strength of a structure is controlled by the presence of stress concentrators such as rivet and fastener holes. The modest reduction in the fatigue strength of aluminium alloys by cladding is insignificant in comparison to the effect of such stress concentrators in the finished structure.

3.2 Galvanic corrosion

To achieve the most efficient aircraft structure it is necessary to use many different materials which are usually in electrical contact. This can lead to the hazard of galvanic or electrolytic corrosion, which can be illustrated by the dramatic increase observed in the rate of corrosion of aluminium alloys in contact with copper-based rivets. While it is theoretically possible to eliminate galvanic corrosion by insulation of one metal from another it is neither possible nor desirable to do so in practice. Electrical continuity must be maintained throughout the bulk of an aircraft structure, and this is most conveniently achieved through rivets and bolts.

Accepting that dissimilar metal contacts are unavoidable the designer needs advice on the dangers. AvP970 provides a guide both to the relative hazards of various bimetallic contacts (see Table 3) and on how safe these contacts can be made both by the use of metallic coatings and by wet assembly, matters dealt with in more detail in the section on protection. Far more detailed information is available in the British Standards Institute publication[3] BS PD6484, in which consideration is also given to carbon metal contacts. It is far safer to use the advice given in PD6484 and in AvP970 than it is to take the do-it-yourself approach of using galvanic corrosion potential differences, such as in Fig 1, to assess the risks of galvanic corrosion. These potential differences indicate the magnitude of the potential hazard but ignore the kinetics of corrosion processes. For example Fig 1 shows that the galvanic corrosion potential difference of aluminium and copper is appreciably less than that of aluminium and a titanium alloy. But aluminium will suffer more severe galvanic corrosion in contact with copper because copper is a more efficient cathode than titanium in a galvanic cell.

4 PROTECTION

Protective measures (paints, metallic coatings, etc) cannot be considered in isolation but must be a part of the total exercise of design and materials selection to prevent corrosion. Because of this approach and the acceptance of the necessity to protect aircraft from corrosion the costs of anti-corrosion treatments are not separated from other materials costs, but these anti-corrosion processes may represent as much at 15% of the total materials bill in UK built aircraft. This may appear to be an unacceptably high price to pay, but the alternative is even less acceptable; an even higher cost-of-ownership bill. Experience in the RAF has shown that economies made in anti-corrosion specifications result in much higher maintenance costs.

The most important aspect of protection is the paint scheme and its application to surfaces pre-treated to ensure good adhesion. Modern aircraft paints are resistant to operating fluids such as kerosene lubricants, hydraulic fluids, de-icing and cleaning liquids, and to water. They resist damage well, are reasonably flexible and perform satisfactorily for well over 10 years on internal structure and for up to 5 years externally. It is unusual to find corrosion on surfaces which have been correctly pre-treated and painted, although aluminium alloys susceptible to exfoliation (those classified D in Table 1) can cause problems. Most cases of corrosion start at fastener holes, at corners and edges, and at faying surfaces, particularly of dissimilar metals, and the problem of total protection is how to extend and maintain a continuous, perfect paint scheme over the whole aircraft structure.

4.1 Protection of individual components

Before considering how to protect a complete aircraft structure it is necessary to look in detail at the protection schemes applied to individual components, and logically a start can be made with the protection of aluminium alloys, the major structural materials in aircraft. The sequence of events and the requirements for protection of aluminium alloys are summarised in Table 4. The essential stage in achieving the maximum performance from a paint scheme is surface pre-treatment. For aluminium alloys it is necessary to clean surfaces by mechanical or chemical means (or a combination of the two) before pre-treatment, which is usually anodising or chromate filming. The choice between these two processes is often determined by considerations other than corrosion prevention; thus, chromic acid anodising is a valuable aid to flaw detection and is generally used for forgings and castings, while chromate filming is assumed to be a less expensive process and can be applied more easily and uniformly to complex structural units. For chromate filming there are several proprietary processes which give conversion coatings about 0.2 μm thick. For anodising a chromic acid process is preferred, the voltage being increased step-wise to 50 V to give an anodic film about 2 μm thick, consisting of a relatively thin, dense barrier coat beneath a thicker, more porous oxide film which is equally suitable for both adhesive bonding and painting. Both bonding and painting operations are carried out on the unsealed anodic film as soon as the film is dry; when both operations are to be applied to one component bonding takes precedence and the anodic film will usually need to be re-activated, prior to painting, by chromate filming.

Painting must follow the pre-treatment within 16 hours, and the first paint coat will invariably be an epoxy primer. A finish coat may also be applied, but at least one coat of primer must be applied before the machining of fastener holes and other recesses which will not be painted, such as those for bushes. The aluminium alloy is protected from the environment not only by the physical barrier effect of the paint film but also by the corrosion inhibiting properties of the chromate pigments which compose at least 20% of the dried primer coat. At any discontinuities the chromate pigment can be extracted from the paint film by water so that the inhibitor can be transferred to the exposed metal surface. Studies of the extraction or leaching of the inhibitor pigment have led to the adoption of strontium chromate as the standard primer pigment in the UK. For high temperature applications barium chromate has a more suitable leach rate[4], although its lower solubility at room temperature makes it unsuitable for use under normal conditions as the sole inhibitive pigment. To ensure acceptable leach rates over a wide range of temperatures a mixture of barium and strontium chromates can be used, or a barium chromate pigmented primer coat can usefully be applied over a strontium chromate pigmented primer on internal structure which does not require a finish coat.

The sequence of events and the requirements for protecting non-corrosion-resisting steels are summarised in Table 5. Cleaning and pre-treatment of steels before painting are both dependent, to some extent, on the strength of the steel: ultra-high-strength steels are so sensitive to hydrogen embrittlement that, in the presence of residual or applied stresses, acidic or cathodic processes can cause cracking. Pre-treatment prior to painting will usually be cadmium coating, either by electroplating or by a vacuum deposition process, with an average thickness of between 4 and 15 μm of cadmium dependent on the size of the component. Alternative pre-treatments can be used when the designer considers that the use of cadmium will cause problems, the main alternatives being aluminium and zinc coatings, and phosphating. As with aluminium alloys the first primer coat of paint must be applied within 16 hours of pre-treatment.

The pre-treatments for aluminium alloys and steels give some degree of protection and can help in delaying the onset of corrosion of the metal when the paint film is damaged. This is especially true of cladding on aluminium alloys which is usually thicker than other sacrificial coatings such as cadmium and zinc coatings on steels. However, the degree of protection is small compared to that obtained from a well applied paint scheme, and the pre-treatments should, above all, ensure good adhesion of the paint primer to the metal substrate.

It is not normally necessary to paint or otherwise protect the more noble or cathodic metal surfaces of titanium alloys, corrosion resisting steels and copper-rich materials.

However, when these noble metals are to be in electrical contact with aluminium or magnesium alloys, or with cadmium plated steel, precautions should be taken to avoid galvanic corrosion of the less noble metal or alloy. One approach is to coat the more noble metal with a sacrificial metal, a metal of lower galvanic potential such as aluminium, cadmium, or zinc (see Fig 1). This reduces the difference in galvanic potential at the contact or, for example, in the case of zinc coatings in contact with aluminium alloys, the coating provides sacrificial protection for the aluminium alloy. There are dangers in this approach. When the aluminium, cadmium or zinc coating corrodes it will eventually expose the underlying (more noble) metal surface in a state in which it is extremely active as a cathode surface, and galvanic corrosion of the less noble metal will be greatly accelerated[5]. A second approach is to paint the cathodic surfaces. In the ideal case this will prevent any galvanic current flow through an electrolyte bridge between the dissimilar metals; in the practical situation where defects are present in the paint films the ratio of exposed cathode to anode surface areas is greatly reduced (compared to the situation where the cathode surface is unpainted) and the corrosion current density at the anode is correspondingly reduced. For maximum protection it is advisable to combine the two approaches, by using both a sacrificial metal coating followed by painting of the more noble metal surfaces.

Carbon fibre composites (CFC) pose an even greater potential problem than noble metal surfaces in the context of galvanic corrosion of aluminium and magnesium alloys and of cadmium plated steel components. Presently, the only technique which can be relied upon to eliminate the galvanic corrosion problem at CFC/aluminium interfaces is adhesive bonding, providing that the glue line is of sufficient thickness to ensure that the two materials are electrically insulated. It is doubtful whether this method can be used in structures containing large quantities of CFC and aluminium alloys because of the requirement to maintain electrical continuity throughout the aircraft structure.

4.2 Protection of magnesium alloys

The protection of magnesium alloy components requires a slightly different approach to that applied to other structural metals and alloys. Firstly, it is difficult to inhibit the corrosion of magnesium; chromates will do so but only when they are present at much higher concentrations than can be achieved by leaching chromate pigments from a paint film. Secondly, all other structural airframe metals are cathodic to magnesium (see Fig 1), which will therefore always suffer galvanic corrosion at unprotected dissimilar metal contacts. For these two reasons it is necessary to encapsulate magnesium alloy components to prevent contact with the environment and, as far as possible, with other metals. Based on the experience of the UK aircraft industry and work on protection of magnesium alloys sponsored by the UK Ministry of Defence the protection requirements are carefully specified in DTD 911. The sequence of events is summarised in Table 6 and starts with mechanical and chemical cleaning processes before chromate filming of the alloy surfaces; certain anodising processes are allowed in place of chromate filming. These surface films are then sealed within 8 hours by application of a stoving epoxy resin; the component is heated at 180°-200°C for 10 minutes before being cooled to 60°C for the application of the resin by a dip and drain procedure. The resin is cured at a temperature of not less than 180°C. The cycle of resin application at 60°C and curing at not less than 180°C is usually repeated twice more, and the total resin film thickness must be at least 25 μm. The resin-coated component is further protected, for example, by one or more coats of epoxy paint primer and one or more coats of paint finish, or by a scheme with a final plastic (*eg* nylon) coating. The minimum total organic film thickness is 100 μm.

Because of the danger of galvanic corrosion of magnesium alloys all surfaces should be protected, at least by sealing with a stoved epoxy resin, before any assembly operations take place. While this is the ideal to be aimed for it is not always achieved either because of overriding design requirements or because of physical damage to the protective scheme during normal assembly operations. Items such as studs and interference fit bushes can be sources of direct metal-to-metal contact, while the assembly of magnesium alloy components into the aircraft structure can result in damage to the protection. Corrosion can be prevented despite these problems if careful attention is given to the sequence of events and the use of specialised materials. For example, maximum use should be made of sealants and caulking compounds which undergo chemical cross-linking; these materials present a barrier through which moisture diffusion is minimised. Also multiple coats of paint should be applied to components after installation in the aircraft if there is any chance of damage to the protection scheme during installation.

4.3 Assembly and final painting

The painting of individual components before they are built up into an aircraft structure is the cornerstone to the protection of the finished article from corrosion. Of equal importance is the use of wet assembly techniques during the building process to prevent water and other liquids from reaching bare metal exposed deliberately (for example, at fastener holes) or accidently, as can occur during assembly operations. Complete wet assembly implies that all contacting surfaces are brought together after being coated with a wet assembly compound, either a sealant or a jointing compound; contacting surfaces include fasteners, both threaded and rivets. Most of the wet assembly compound will be squeezed out during assembly, but it should fill any crevice and it will leave a bead of material around the join line of the mating surfaces. Wherever possible sealants which undergo chemical cross-linking after assembly are preferred, and are essential in fuel tank and pressure cabin areas. The most widely used materials are polysulphides, cross-linked to give sealants which are elastomeric down to -60°C, and capable of operating for the life of the airframe at temperatures up to 120°C. For higher temperature applications (for example, in areas close to heat sources and on supersonic transport aircraft) fluorocarbons, which are elastomeric down to -15°C and with a useful service life up to 200°C, are used. Jointing compounds, non-setting materials, are used mainly in areas where disassembly will be required for routine servicing and sealants would cause problems.

Painting after assembly varies according to the environment that the particular part of the structure will see (Tables 4 and 5). Internal surfaces which will not be subjected to condensation or contamination can be protected with a single coat of paint primer. However, it is necessary at least to re-prime over all fastener areas and make good any locally damaged paint; preferably the surfaces should be re-primed overall. For heavy duty internal surfaces it is necessary to re-prime over fastener areas and make good any damage before applying either a finish coat or a further coat of primer paint. External surfaces should be re-primed, at least over fastener areas, before application of the finish coat. In all cases if there has been a long time delay between priming and application of subsequent paint coats it is necessary to lightly abrade the primer coat to ensure good intercoat adhesion; and to give adequate protection a refresher coat of primer must be applied over the abraded original primer coat.

The standard exterior finish for UK military aircraft is a solvent drying acrylic paint. This was adopted in 1975 in preference to the previously used polyurethane finish. The change in policy was made for several reasons: acrylic finish coats can be selectively removed with mild chemical paint removers to leave the epoxy primer coat intact; acrylic finishes are easier to repair by touch-up procedures; the polyurethane paint finishes had not shown the durability in service for which reason they had originally been used, and do tend to crack and chip rather easily. However, aircraft which use synthetic hydraulic fluids are still finished in polyurethane. Irrespective of the chemical type of finish, the exterior surfaces of operational aircraft are matt for camouflage purposes while internal paint finishes should be glossy and light coloured to aid inspection.

Mention should be made of etch or wash primers. They are allowed as alternatives to chromate filming or anodising as a pre-treatment on aluminium alloys before the primer paint is applied, although they should not be used where resistance to synthetic oils or hydraulic fluids is needed. In general, etch primers are not used to a great extent in the UK aircraft industry, nor does the RAF use them a great deal for re-surface finishing, despite the apparent advantage of using an etch primer in place of chromate filming on an aircraft structure. This reticence is probably because paint failures, particularly those involving filiform corrosion, have often been associated with the use of etch primers. However, in the past etch primers were sometimes used as the sole primer, in contrast to the present requirements which only allow their use as a pre-treatment, and it is possible that their poor image is to some extent due to this type of usage.

4.4 Problem areas

The sequence of events described of painting (at least to the primer stage) before wet assembly, followed by further paint treatment, is a very satisfactory and sound method of protecting an aircraft structure. However, the success or failure of the protection scheme is very dependent on the skill and commitment of those involved in ensuring that the excellent materials and processes are correctly applied. This is particularly so in use of jointing compounds and sealants, an essential but very messy part of the protection scheme. Valuable improvements would be development of materials which can be applied under less than ideal conditions. especially for use in repair and re-work situations, and which are less objectionable to the operator.

In an ideal world the protection schemes applied to individual components, at assembly and following assembly, should ensure a corrosion-free life to aircraft structures. In the real world, situations occur which prevent the ideal from being realised. This is especially so in the case of moving parts, such as in undercarriage components when dissimilar metal contacts occur under conditions where contamination by water and operating fluids is a common problem. Aluminium alloys with load-bearing ferrous metal inserts often suffer galvanic corrosion, while the moving parts (usually ferrous metal bearing surfaces) are commonly protected by greases which may harden and dry out between scheduled services. To prevent galvanic corrosion ferrous metal inserts should be cadmium plated, but for bearing surfaces a hard finish (such as hard chromium plating) is required. Also, these ferrous metal inserts are usually pressed into untreated aluminium alloy recesses with only jointing compound or other void-filling wet assembly materials to prevent crevice corrosion at the mating surfaces. Although painting after assembly provides additional protection, the integrity of surface protection is difficult to maintain under the normal operating conditions of undercarriage structures. More flexible paint schemes could provide additional protection, but only if the increased flexibility is not gained at the expense of fluid resistance.

Corrosion can occur in hollow structures which are not completely sealed, especially tubular steel structure. It is difficult to achieve adequate surface pre-treatment in these cases, so that subsequently applied protection schemes may not adhere. There are materials which can be utilised by fill-and-drain processes, for example, solvent-drying nitrile rubber coatings which adhere well to surfaces which are not perfectly clean, and wax-based supplementary protectives of the type used to protect hollow members in automobile structures. These materials are used in other areas of aircraft structures to supplement the normal protective schemes: in integral fuel tanks the nitrile rubber-based materials are used to protect the polysulphide sealants from water and fuel attack, while the wax-thickened materials are often applied, after a dewatering compound, to supplement the normal paint schemes in internal structure, particularly in bilge areas.

Modern paint schemes will protect aircraft structure for long periods of time, and repainting of external structure is only necessary after 3-5 years. This repainting often entails only scuffing back the finish coat in the case of polyurethane paints or removing acrylic finishes by selective chemical paint removers before applying a refresher coat of primer and new finish coat. However, the paint schemes currently used are fairly rigid and tend to crack or chip, the problem being most noticeable on the upper wing surfaces of large transport or reconnaissance aircraft, especially around the heads of fasteners. To alleviate this problem more flexible paint schemes have been developed, although the increase in flexibility is only obtained at the expense of solvent resistance. One of the most successful flexible paint schemes utilises either a primer or an intermediate coat of the same polysulphide polymer as that usually employed as a sealant for wet assembly purposes[6]. However, these materials are relatively dense and are applied in coatings up to 200 μm thick. The weight penalty involved is unacceptable in many cases, and various flexible paint schemes, applied at more conventional thicknesses of 25-50 μm per coat, are currently being evaluated.

The use of structural adhesives can cause problems in painting operations. To obtain the maximum performance from both adhesive and paint, the surface pre-treatment must be kept clean and the adhesive or paint applied within 16 hours of pre-treatment. To achieve good cohesive strength in a bonded structure the adhesive must be applied directly to the pre-treated surface. This leaves a problem for the painting operation. The surface pre-treatment outside of the bonded areas is adversely affected by the bonding procedures, by a combination of the curing cycle, by the necessary handling operations, and by the time elapsed between pre-treatment and the component's availability for painting. To achieve reasonable paint adhesion it is necessary to re-treat the unbonded surfaces with a chromate-filming solution. An alternative approach is to use an adhesive primer prior to the bonding operations, so that subsequent application of paint is only preceded by a degreasing operation, or light abrasion of the adhesive primer surface. It is hoped to initiate work which will resolve the problems of pre-treatments for both adhesive bonding and painting operations.

5 CADMIUM AND CHROMATES

Two important materials used in preventing corrosion in aircraft structures are cadmium and chromate salts. Cadmium is used to protect steel components, to prevent galvanic corrosion at what would otherwise be unacceptable dissimilar metal contacts (aluminium/copper, for example), and in electronic components for its dual function of preventing corrosion and as an aid to soldering. Chromate salts are used as corrosion inhibitors, their most valuable role being as pigments in paint primers, but also in several metal pre-treatment operations such as chromic-sulphuric acid pickling, chromate filming and chromic acid anodising of aluminium alloys, passivating of cadmium and zinc surfaces, and chromate filming of magnesium alloys. Both cadmium and chromates are health hazards so great care must be exercised in their manufacture and use to prevent contamination of the environment.

5.1 Cadmium plating

Cadmium has been in widespread use for little over 30 years but it has been released into the environment for a much longer period, locally in the manufacture of zinc and other metals, and more generally by the burning of coal. Losses of cadmium to the air, the land and to water sources has undoubtedly increased with the increased use of cadmium, not only its use in preventing corrosion but also in pigments in stabilisers for plastics, in batteries and in other minor areas. Little information is available regarding the increase in the level of cadmium pollution; one study[7] indicates that the level of cadmium layed down in ice layers preserved in glaciers has at least quadrupled in the period 1870 to 1970. Present day pollution occurs mainly when cadmium-containing materials are disposed of; pollution can be initially to the air during incineration of waste or reclaiming of ferrous scrap, or to the land and water sources when waste is disposed of as landfill material, the gradual leaching of which releases cadmium salts.

The uptake of cadmium by man is mainly from food, especially vegetables and cereals, and from cigarette smoking; uptake from water is less significant. Excretion of cadmium is generally less than the rate of absorption and accumulation results, especially in the kidneys and liver. Because cadmium is toxic and does not appear to serve any essential biological function it is sensible to restrict man's intake to a minimum, which implies reducing to a minimum the release of cadmium to the environment. More work is required to establish threshold concentrations in the body, particularly in the kidney, and to quantify the other possible toxic hazards of cadmium. Presently the average intake through the food chain in the UK is well within the provisional maximum tolerable limit (400-500 μg per week), recommended by the World Health Organisation[8].

Electroplating accounts for about one third of cadmium usage at the moment in the UK, and within the non-communist world, and anti-pollution measures are necessary to minimise the cadmium content of effluent from electroplating facilities, both water effluent and cadmium-containing sludge. However, even the most stringent control during manufacture of cadmium and its deposition will not prevent the main source of pollution, the use and disposal of the finished article. There is, therefore, a very powerful argument to limit the use of cadmium plating and to seek alternatives for the protection of steel. To this end in the UK an Industry/Government Working Group has been set up to advise on how a 50% reduction in the usage of cadmium plating can be achieved, while taking account of the technical advantages of cadmium.

It is important to recognise the special properties, indeed the unique combination of properties[9], of cadmium when considering possible replacement coatings. The obvious candidates as replacements are zinc and aluminium, but neither is comparable with the total package of properties exhibited by cadmium, namely, surface lubricity, solderability, galvanic compatibility with aluminium alloys, electrical conductivity, and the non-binding nature of corrosion products. In many applications one or more of these qualities of cadmium may not be required, and it may be quite acceptable to use zinc or aluminium coatings. With this in mind the requirements for the protection of steel components have been amended in the latest draft revision of Chapter 801 of AvP970: whereas previously cadmium plating was required it is now acceptable for the designer to specify zinc or aluminium coatings where the special properties of cadmium are not all required. However, for fasteners cadmium is still required because of the excellent lubricity of the coating and non-binding nature of its corrosion products. There appear to be no major problems in meeting this demand, or indeed any requirement for cadmium plating in the UK, and there are probably well over 100 companies able and willing to cadmium plate.

Despite the technical arguments for retaining cadmium plating it is possible that a change will be forced upon the aviation industry by legislation similar to that which comes into effect in July 1982 in Sweden. This legislation will prohibit, with certain exceptions, the importation of products containing cadmium. The exceptions may well allow the importation of aircraft or aircraft components containing cadmium plated items, but the situation is not completely clear. And this legislation may be only the forerunner of more severe restrictions in Sweden or other countries. At the present time there is no suitable alternative to cadmium for the protection of all steel components, and its use should be defended strongly. At the same time research to find a suitable replacement coating should be encouraged. Of the alternatives to cadmium aluminium appears to be the most promising although presently available processes produce pure aluminium coatings which have some major weaknesses. The most important is the apparent inability to protect steel sacrificially in a chloride ion environment: coated fasteners show red rusting within weeks of exposure to the atmosphere in the vicinity of the sea[5]. In attempts to improve their properties work sponsored by the MOD is proceeding in the UK to develop improved aluminium coatings and coatings of aluminium containing small amounts of zinc and other alloying elements. These alloy coatings should cathodically protect steel far more satisfactorily. One attraction of aluminium and aluminium-rich coatings is that a common pre-treatment of fastener coating and aluminium alloy structure could then be adopted. A uniform pre-treatment, such as chromate filming, should give optimum paint adhesion, and thus overcome one of the few complaints about cadmium plating, the occasional poor paint adhesion, especially to the heads of fasteners.

5.2 Chromate salts

Chromates are unique amongst presently used corrosion inhibitors in their ability to suppress corrosion of aluminium alloys under a wide range of conditions. They are also very effective inhibitors of corrosion for steels, cadmium and zinc, and probably the most effective compounds in the most difficult task of inhibiting the corrosion of magnesium alloys. For aluminium alloys, experience in the UK suggests that the best pre-treatments are chromic acid anodising and chromate filming, while the protection of magnesium alloys is founded on chromate filming or anodising in chromate containing solutions. It would be difficult to imagine a scenario without chromates in the protection of aircraft structures.

The major objection to chromate salts is their toxicity and carcinogenicity when chromate-containing particles are inhaled. Other objections concern the effects of chromates when absorbed through the skin, especially broken skin. Chromate salts can destroy useful bacteria and interfere with normal sewage disposal systems, and they must not be allowed to pollute surface water or sewage waste. The necessary control of effluent is not difficult and does not present a problem any greater than that associated with precipitation of any other metal ions from effluent water. The major problem associated with chromate salts arises in their manufacture and subsequent use, when they can present a major hazard to personnel involved, and it is questions concerning the future manufacture of the anti-corrosive chromate pigments which threaten their future use for corrosion prevention purposes.

If the various pre-treatment processes for which chromates are presently required are examined individually it is possible to devise alternative schemes, although some would not be accepted as totally effective alternatives. It is the use of chromate pigments in paints, and to a lesser extent in wet assembly compounds, caulking compounds and as inhibitor cartridges or tablets, that it is most difficult to visualise acceptable alternatives. A possibility is to abandon the concept of incorporating inhibitive pigments in paint schemes and to rely on a combination of barrier coats; for example, to rely on cladding or coating of all aluminium alloy parts with aluminium or an aluminium - 1% zinc alloy, combined with a stoved, highly impervious organic coating. By analogy, the use of a stoved barrier coat on magnesium alloy followed by nylon coating can be extremely effective, although coating weight is considerably greater than that of current aircraft paint schemes.

A more acceptable solution would be to use an inhibitor of similar efficiency to the chromate ion. In the UK a large proportion of the MOD air-side research effort in corrosion prevention is aimed at understanding the mechanism by which inhibition of aluminium occurs, and to investigating alternative materials. In the past attempts have been made to evaluate inhibitors for aluminium, and the approach has usually involved determining inhibitor efficiency in chloride ion solutions, usually at concentrations of between 1% and 5% sodium chloride. In recent work at RAE[10] it was shown that very dilute sodium chloride solutions (less than 100 ppm) can be more corrosive, in terms of weight loss of aluminium alloys, than more concentrated solutions (1% or 3.5% sodium chloride). Consequently, a range of chemicals usually considered to be useful inhibitors were evaluated by using them in solutions of 58 ppm sodium chloride. Surprisingly, many of the materials enhanced the corrosion, particularly in terms of promoting pitting corrosion. However, one chemical investigated, the zinc salt of thioglycollic acid, appeared to be as effective as chromate salts in inhibiting the corrosion of aluminium.

Further work is proceeding to examine thioglycollic acid derivatives as possible replacements for chromate salts, and results are extremely promising. However, thioglycollate salts react with the normal epoxy resin systems used in paint primer formulations, and much more work will be necessary before these very promising inhibitors could be considered as suitable paint pigments.

6 CONCLUSIONS

Corrosion control measures must be considered during the design of aircraft and associated equipment. The detailed design of components and of the total structure must take into account the need to keep the finished aircraft free of potentially corrosive materials by adequate sealing, draining and venting. Materials selection must take into account the corrosion resistance of the individual materials and of combinations of materials. Necessary protection procedures can only be used to maximum advantage by considering them together with detailed design and selection of materials.

Presently used protection methods are adequate in most situations provided that they are carried out correctly. Improvements are possible by developing materials which can be applied more easily and under adverse conditions, by consideration of paints which are more resistant to mechanical damage, and by examining pre-treatments which are suitable for combined adhesive bonding and painting operations.

It is possible that health and safety considerations will restrict the choice of corrosion prevention processes and two materials for which replacements could be needed are cadmium and chromates. Considerable research effort is currently directed towards these two problems. Until satisfactory replacements are developed the technical case for the continued use of cadmium coatings and chromate inhibitors should be promoted by the aerospace community.

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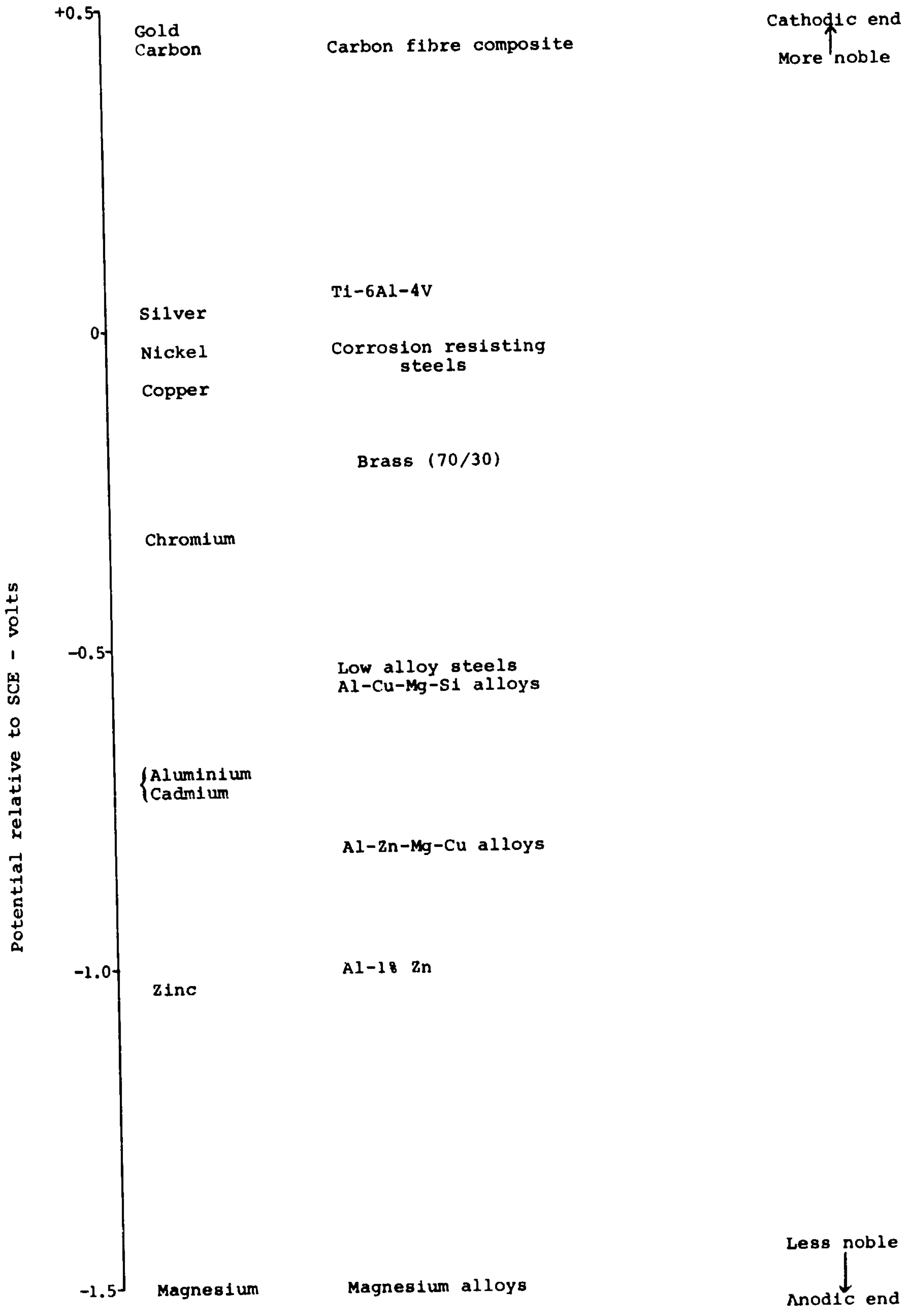


Fig 1 Galvanic potentials in chloride ion solutions

Table 1

RELATIVE SUSCEPTIBILITIES TO EXFOLIATION CORROSION OF VARIOUS WROUGHT ALUMINIUM ALLOYS

Alloy type and temper		Sheet <3.2 mm		Sheet ≥3.2 mm section	Plate		Tube		Extruded bar and section		Forgings	
2014	T3, T4	BS L108 BS L156 BS L158 BS L163 BS L164	B/C	D			BS L105	D	BS L102	D	BS L103	D
	T6	BS L157 BS L159 BS L165 BS L167	B/C	B/C	DTD 5040 BS L93	C C	BS 3L63	C	BS L168 BS 3L87	C C	BS 2L77	B/C
2618	T6	DTD 5070	B	B	2618-T651	B			DTD 5014 2618-T6, T62	B/C B/C	DTD 717 DTD 731 DTD 745	C B B
	T71										DTD 5084	B
2219	T6						2219-T62	B/C	2219-T62	B/C		
	T8				2219-T851	B	2219-T851	B/C	2219-T8510	B/C		
2024 (2124)	T3, T4	BS L109 BS L110	B/C B/C	D D	DTD 5100 BS 2L97	D D						
	T8				2024-T851	B						
6082	0	DTD 346	A/B	A/B								
	T6	BS L113	A	A	BS L115	A/B	BS L114	A/B	BS L111	A/B	BS L112	A
6061	T6						BS L117 BS L118	A A				
7010	T76				DTD 5120	B						
	T736				DTD 5130	A/B					DTD M239	B
7050	T76				7050-T7651	B						
	T736				7050-T73651	A/B					7050-T736	B
7075 (7175) (7475)	T6	BS 2L88	D	D	DTD 5110 BS 2L95	D D			DTD 5074 DTD 5124	D D		
	T73				7075-T7351	A			BS L160	A	BS L161 BS L162	A A
7XXX	T6								DTD 5114	D	DTD 5024	D
	T7										DTD 5104	C

NOTE 1: The susceptibility of 2000 series (aluminium-copper) alloys are markedly affected by grain structure, which is dependent on the amount of working and the quench rate experienced by the alloy. In general, the thinner section materials will be categorized B and susceptibility will increase with section to category C: this is indicated by B/C ratings.

NOTE 2: The susceptibility of forgings is very dependent on the degree of working. Those categorized D may occasionally be used quite safely and the use of one of the tests for exfoliation corrosion is recommended to assist the Project Director in assessing the case for using the alloy.

CLASSIFICATION OF SUSCEPTIBILITY

A Immune to exfoliation corrosion.

B Resistant to exfoliation corrosion, although mild exfoliation may be induced under the most extreme conditions.

C Susceptible to exfoliation corrosion. Under some conditions exfoliation can occur in service. Alloys in this category should only be used after discussion with materials specialists.

D Very susceptible to exfoliation corrosion. These alloys shall not be used without the prior approval of the Aircraft Project Director.

Table 2

RELATIVE SUSCEPTIBILITIES TO STRESS CORROSION CRACKING OF VARIOUS STEELS

Alloy type	Maximum specified tensile strength in range (MPa) Over	Not over	Bars and forgings		Only for bolts (etc)		Sheet and plate		Tube		Castings	
Non-corrosion resisting mild steels & low/medium alloy steels	-	1450	BS S91 BS S95 BS S98 BS S99 BS S131 BS S139 BS S140 BS S142 BS S154	A A B B A A A A A	BS S147 BS S149	B B	BS S534 BS S535	A B	BS T53 BS T60 BS T65	A B A	BS HC3 BS HC4 BS HC7 BS HC8	A A B C
	1450	1550	-	-	-	-	-	-	-	-	-	-
	1550	1800	BS S134	C	-	-	-	-	-	-	-	-
	1800	-	BS S135 BS S136 BS S138 BS S146 BS S155 (300 M var)	D D C D D	DTD 5222	D	-	-	-	-	-	-
Maraging steels	1800	-	DTD 5212	D	-	-	(New spec)	D	-	-	BS HC401	D
Nitriding/ carburising steels	-	1450	BS S106 BS S133	A B	-	-	-	-	-	-	BS HC5 BS HC6	A B
	1450	1550	BS S132 (S82 type)	B B	-	-	-	-	-	-	-	-
Precipitation hardening steels	-	1450	BS S143 BS S144	B B	-	-	BS S530 BS S531 BS S533	B B B	-	-	BS HC101	B
	1450	1550	BS S145	C	-	-	-	-	-	-	BS HC102 BS HC106	C C
	1550	1800	-	-	-	-	-	-	-	-	-	-
	1800	-	-	-	-	-	-	-	-	-	-	-
Other corrosion and/or heat resisting steels	-	1450	BS S80 BS S129 BS S130 BS S137 BS S152	B A A B B	DTD 5076	B	BS S524 BS S525 BS S526 BS S527 BS S536 BS S537 BS S538	A A A A A A B	BS T66 BS T67 BS T68 BS T69 BS T72 BS T73 BS T74 BS T75 (21.6 9 type)	A A A A A A A A	BS HC104	A

NOTE: Many steels, including some low strength steels, are susceptible to stress corrosion cracking in hot caustic and nitrate solutions. Steels immersed in hydraulic fluid or oil may be so protected, and even category D materials may be safely used.

CLASSIFICATION OF SUSCEPTIBILITY

A Very resistant to stress corrosion cracking in commonly encountered environments.

B Resistant to stress corrosion cracking. When pre-existing cracks or defects are present, failures may occur under sustained tension stresses in wet environments. This group of alloys can often be used without many stress corrosion design limitations. The normal protective treatments applied to stop rusting also give good protection against stress corrosion.

C Susceptible to stress corrosion cracking. Stress corrosion cracking of these steels can be expected unless the appropriate precautions are taken at the design stage. Steels in this category should only be used after discussion with structures and materials engineers.

D Very susceptible to stress corrosion cracking. The use of steels in category D is restricted and is only permitted with the approval of the Aircraft Project Director.

Table 3

DEGREE OF CORROSION AT BIMETALLIC CONTACTS

Where a metal is plated, the behaviour should be sought under that of the plated coating

Class A *The corrosion of the first metal is not increased by the second metal*

Class B The corrosion of the first metal may be slightly increased by the second metal

Class C The corrosion of the first metal may be markedly increased by the second metal

Class D The corrosion of the first metal may be very seriously increased by the second metal

	First metal \ Second metal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Gold platinum, rhodium, silver	Monel Inconel, nickel/ molybdenum alloys	Cupronickles, silver solder aluminium-bronzes, tin-bronzes, gunmetals	Copper brasses, 'nickel silvers'	Nickel	Tin and soft solders also lead	Steel and cast iron	Cadmium	Zinc	Magnesium and magnesium alloys (chromated)	Stainless steels: Austenitic 18/8 Cr/Ni	Stainless steels: 18/2 Cr/Ni	Stainless steels: 13% Cr	Chromium	Titanium	Aluminium and aluminium alloys
1	Gold, platinum, rhodium, silver	-	A	A	A	A	A	A	A	A	A	A	A	A	A	A(r)	A
2	Monel, Inconel, nickel/ molybdenum alloys	B	-	A	A	A	A	A	A	A	A	A	A	A	A	A	A
3	Cupronickels, silver solder, aluminium-bronzes, tin bronzes, gunmetals	C(f)	B or C	-	A	A	A	A	A	A	A	B or C	B	A	B or C	B or C	A(c)
4	Copper, brasses, 'nickel silvers'	C(f)	B or C	B or C	-	B or C	B or C(k)	A	A	A	A	B or C	B or C	A	B or C	B or C	A(c)
5	Nickel	C	B	A	A	-	A	A	A	A	A	B or C	B or C	A	B or C	B or C	A
6	Tin and soft solder, also lead	C	B or C(m)	B or C	B or C	B	-	A	A	A	A	B or C	B or C	B or C	B or C	B or C	A
7	Steel and cast iron	C	C	C	C	C(f)	C(f)	-	A(g)	A(g)	A	C	C	C	C(f)	C	B(g)
8	Cadmium	C	C	C	C	C	B(n)	C	-	A	A	C	C	C	C	C(q)	B
9	Zinc	C	C	C	C	C	B	C	B	-	A	C	C	C	C	C	C(e)
10	*Magnesium and magnesium alloys (chromated)*	D	D	D	D	D	C	D	B or C	B or C	-	C	C	C	C	C	*B or C(s)*
11	Stainless steel: Austenitic 18/8 Cr/Ni	A	A	A	A	A	A	A	A	A	A	(p)	A	A	A	A	A
12	Stainless steel: 18/2 Cr/Ni	C	A or C(l)	A or C(l)	A or C(l)	A	A	A	A	A	A	A	(p)	A	A	(j)	A
13	Stainless steel: 13% Cr	C	C	C	C	B or C	A	A	A	A	A	C	C	(p)	C	C	A
14	Chromium	A	A	A	A	A	A	A	A	A	A	A	A	A	-	A	A
15	Titanium	A(r)	A	A	A	A	A	A	D(q)	A	A	A	A	A	A	-	A
16	Aluminium and aluminium alloys (h)	D	C	D(c)	D(c)	C(f)	B or C	B or C	A	A	A(d)	B or C	B or C	B or C	B or C(b)	C	(h)(p)

NOTES TO TABLE 3:

(a) Where contact between magnesium and aluminium alloys is necessary, the use of aluminium alloys with low or negligible copper content is preferred.

(b) In contact with thin (decorative) chromium plate, the symbol is C, but with thick plating (as used for wear resistance) the symbol is B.

(c) When contacts between copper or copper-rich materials and aluminium alloys cannot be avoided, a much higher degree of protection against corrosion is obtained by first plating the copper-rich material with tin or nickel and then with cadmium, than by applying a coating of cadmium of similar thickness. The aluminium in contact with the copper-rich material should be anodised when practicable.

(d) When magnesium corrodes in sea-water or certain other electrolytes, alkali formed at the aluminium cathode may attack the aluminium.

(e) When it is not practicable to use other more suitable methods of protection, *eg* spraying with aluminium, zinc may be useful for the protection of steel in contact with aluminium, despite the accelerated attack upon the coating.

(f) This statement should not necessarily discourage the use of the second metal as a coating for the first metal provided that continuity is good; under abrasive conditions, however, even a good coating may become discontinuous.

(g) In these cases the second metal may provide an excellent protective coating for the first metal, the latter usually being electrochemically protected at gaps in the coating.

(h) When aluminium is alloyed with appreciable amounts of copper it becomes more noble and when alloyed with appreciable amounts of zinc it becomes less noble. These remarks apply to bimetallic contacts and not to the inherent corrosion resistance of the individual aluminium alloy. Such effects are mainly of interest when the aluminium alloys are connected with each other.

(j) No data available.

(k) In some immersed conditions, the corrosion of copper or brass may be seriously accelerated at pores or defects in tin coatings.

(l) Serious acceleration of corrosion of 18/2 stainless steel in contact with copper or nickel alloys may occur at crevices where the oxygen supply is low.

(m) Normally the corrosion of lead-tin soldered seams is not significantly increased by their contact with the nickel-base alloys but under a few immersed conditions the seams may suffer enhanced corrosion.

(n) Tin should not be used in contact with cadmium in joints liable to be heated above 120°C.

(p) Joints liable to crevice corrosion when the oxygen supply is limited.

(q) Under some circumstances cadmium can penetrate titanium alloy and embrittle it; a warning of the danger is given in Leaflet 801/1.

(r) There is evidence that at elevated temperatures in certain atmospheres (*eg* exhaust gases), silver coatings may cause cracking of stressed titanium alloy parts.

Table 4

PROTECTION OF ALUMINIUM ALLOYS

1 Cleaning	One or more of the following:	
	(a) Degrease	DEF STAN 03-2 Method A
	(b) Alkaline clean	Method B2
	(c) Abrasive clean	Method D
	(d) Pickle or etch	Methods N and O
2 Pre-treatment	One or more of the following:	
	(a) Anodise	DEF 151, preferably type 2
	(b) Chromate film	DEF STAN 03-18
	(c) Etch prime	DEF STAN 80-15 and DTD 5555
3 Paint primer	Epoxy	DTD 5567
4 Paint finish	(a) Interior surfaces	Minimum requirement 20 µm coat of primer. For most purposes two coats (40 µm) of primer or requirements as for exterior surfaces
	(b) Exterior surfaces	Minimum requirement is 20 µm coat of primer plus 30 µm coat of acrylic finish to DTD 5599
	(c) Interior and exterior surfaces where high resistance to polar liquids is required	Minimum requirement is 20 µm coat of primer plus 30 µm coat of polyurethane finish to DTD 5580

Table 5

PROTECTION OF NON-CORROSION-RESISTING STEELS

1 Cleaning	Various methods are allowed, depending on strength of steel	DEF STAN 03-2 DEF 162 for steels of minimum specified TS over 1400 MPa
2 Pre-treatment	Cadmium	DTD 904 DTD 940 for steels with maximum specified TS over 1450 MPa
	Alternatives to cadmium:	
	(a) Aluminium	BS 2569 part 1
	(b) Zinc	DTD 903
	(c) Phosphating	DEF STAN 03-11 Class I or II
3 Paint primer	Epoxy	DTD 5567
4 Paint finish	Dependent on position in aircraft, as in the protection of aluminium alloys	DTD 5567 DTD 5580 DTD 5599
5 Stoving enamel	To replace 3 and 4 where ultra high performance paint scheme is needed	BS X31 DTD 56

Table 6

PROTECTION OF MAGNESIUM ALLOY CASTINGS

1 Cleaning	(a) Preliminary cleaning (die-castings may not require preliminary cleaning) (b) Fluoride anodising	DEF STAN 03-2 Method D1 Alternatively rough machining, scurfing, pickling or chemical milling DTD 911
2 Pre-treatment	(a) Hard anodising, or:- (b) Fluoride film removal followed by chromate filming	DTD 911 - HAE or Dow 17 processes DTD 911 - Two processes for fluoride film removal and three for chromate filming are allowed
3 Surface sealing	Epoxy resin sealing which may be chromate pigmented	DTD 5562 - Resin specification DTD 935 - Process specification. Minimum film thickness 25 μm
4 Further protection	(a) Etch primer which may be applied if required (b) Epoxy primer (c) Finish coats	DEF STAN 80-15 DTD 5555 DTD 5567 (or approved alternative) DTD 5567 - Epoxy DTD 5580 - Polyurethane or other approved paint finish or organic coating (*eg* nylon coating). Minimum total organic coating to be 100 μm thick

CORROSION PREVENTION METHODS DEVELOPED FROM DIRECT EXPERIENCE WITH AEROSPACE STRUCTURES

by

Dr. Ing. M. Scolaris
Director of Aeritalia G.V.C. Laboratories
Corso Marche 41
10146 - Torino - Italy

SUMMARY

Some examples of various types of corrosion experienced during hardware service are reviewed and the significant remedial action adopted first to repair and then to eliminate the problem are presented.

The changes in design incorporated during design development as a function of the experience and technical knowledge acquired are presented.

Some examples of effective protection validated through service life are illustrated. The present trends for effective corrosion prevention are also illustrated.

1. INTRODUCTION

Continuous evolution of design techniques and calculation methods, constantly improved knowledge of fatigue and fracture mechanics phenomena, improved quality of materials and of manufacturing techniques, development of better inspection equipment and increased reliability of the inspections as well as availability of ever more complete technical and experimental data have resulted on the attainment of a significant increase of the operating life of most of aerospace vehicles which, for example, for commercial aircraft is now measured in tens of years.

Because of the above, the problem of protecting aircraft structures from corrosion has actually become one of the most critical, and ever increasing attention is being paid to it by all concerned.

The designers find themselves in need to have to identify, for each individual application, the best methods of corrosion prevention and, since these vary not only according to the materials to be protected but also in relation to the manner with which these materials are exposed to conditions conducting to corrosion and these in turn are functions of the material as well as of the local design configuration, they must gather sufficient data about the aircraft in-service behaviour in order to be able to make the best possible choise.

Notwithstanding the most carefull engineering, unforeseen situations may sometime occur, which will require corrections and/or modifications of aircraft already in service and design improvements for the new ones.

New metallic materials are continuously proposed for aircraft use by the producers, to stay ahead of competitor as well as to counter pressing competition of plastic materials.

However, the superior performance of the new alloys proposed must never be considered apart from their capability to resist to the various types of corrosion, the determination of which requires an adequately complete and long experimentation.

On the other hand, also materials believed to be well known may reserve surprises, since local factors such as design configuration, surface treatment, mode of assembly, ambient conditions, etc. may determine critical situations not evidenced by the standard experimentation accomplished.

These considerations evidentiate the need to bring about the evolution of theoretical and experimental knowledge also as a function of the direct experience progressively accumulated with the in-service aircraft.

One indication of how varied and diversified may be the aspects of the better known types of corrosion on aerospace materials is given by the listing below, where the particular type of corrosion associated with each definition has been amply documented both experimentally and theoretically and is covered by specialized leterature.

- Pitting corrosion
- Galvanic corrosion
- Exfoliating corrosion
- Stress corrosion
- Fretting corrosion
- Corrosion fatigue
- Surface corrosion
- Intergranular corrosion
- Filiform corrosion
- Crevice corrosion
- Microbiological corrosion

It must be remembered that these phenomena may and do occur in combination of two or more types of corrosion present on the same area.

The techniques for surface protection best suited to hinder initiation of corrosion, even if in constant evolution, have reached a marked degree of efficiency, however, since it is not always possible to adopt, starting right from the design phase, either the use of materials not subject to corrosion, or surface protections capable of maintaining their efficiency throughout the entire aircraft operating life, each aerospace industry is in possess of records, sometime quite large, of examples of corrosion occured on its in-service aircraft and of the actions taken to keep them in check. Such records are therefore a useful supply of experimental data for designers, metallurgists, laboratory technicians and inspectors concerned.

They also serve to integrate official regulations, technical pubblications and specifications supplied by most producers of materials, which necessarily have a more general character.

Examination of records about corrosion occurred in service permits a direct contact with the real conditions to which phenomena of different nature are associated and constitute a sure reference, both for structure design and for compilation of inspection and maintenance manuals that must be provided for each type of aircraft.

Aeritalia like other Companies has recorded a series of experiences with phenomena of corrosion occurred on aircraft of its own production, as well as on aircraft on which it carries out periodic maintenance for other Aerospace Industries or Commercial Carrier Companies. Such data must always be considered when deciding corrective actions to be adopted both to reconstruct the original structural efficiency and/or to prevent repetition of the same corrosion phenomena.

In addition a file has been built of the records of solutions to corrosion problems particularly significant, most of these solutions have already been incorporated on original design and have proved themselves to be valid also for in-service aircraft.

Purpose of this paper is to document some of the above mentioned Aeritalia experiences which are believed to be of interest because they are representative of the more common cases of corrosion.

The present design tendency for an ever more accurate protection of structures from corrosion are also presented, with due consideration being given to the request for increased aircraft in-service operating life and to the ever greater diffusion of advanced composite materials. With the practical use of these last ones new problems are associated and these problems are quite different from those proper of the traditional metallic materials.

2. CASES OF IN-SERVICE CORROSION

In the course of inspection of aircraft structures damage by corrosion may be found, either visually or with non destructive test methods. In such cases, it is necessary to implement actions adequate to:

a) Identify the causes of phenomena

b) Identify its possible presence on other aircraft of the same type

c) Repair the damage found (whenever the structural part concerned must not, or cannot be replaced)

d) Inhibit, through adequate "ad hoc" protection, repetition of the corrosion phenomena (possibly for the whole remaining operating life of the aircraft concerned)

e) Introduce the necessary design modifications to eliminate, or at least to reduce, the sensitivity to corrosive conditions for analogous structures of aircraft yet to be manufactured or of replacements for damaged ones.

The experience has demonstrated that while most of the aircraft structural parts may be subject to corrosion, the phenomenon occurs with higher velocity and greater intensity on areas directly exposed to atmospheric agents, or near points where humidity infiltrations are possible, or in areas where stagnation of some substances capable of acting as corrosion initiators occurs; and it is less likely to occur on areas with no exchange of air with external atmosphere such as for example, sealed bays that do not contain humid air.

A graphic presentation of the more critical areas, from this point of view, is shown on figure 1.

The cases of corrosion quoted hereafter have been drawn from Aeritalia records and are described as examples. Both the causes origin of corrosion and the consequential remedial actions developed are specified.

2.1. - Corrosion on wing and fuselage skins

These surfaces, in addition to being subjected to in-flight mechanical stress, are also influenced by ambient conditions such as: atmospheric humidity, sometime associated with high salinity with possible stagnation of moisture inside cavities not airtight toward the exterior; ambient air containing corrosive agents discharged from industrial activities, thermal shocks, etc.

These ambient conditions are conductive to corrosion phenomena, which starting either from external surfaces or from internal ones subject to moisture stagnation or to other local negative factors, may then rapidly propagate themselves to other areas of the structures.

As examples are quoted pitting, filiform, intergranular and exfoliation corrosion cases.

In the case of corrosion by exfoliation shown at figure 2 corrosion started at the fastener locations and progressively involved, in depth the material.

In fact, even if adequate protection had been prescribed and applied after the component machining, some local interruption of it, due to assembling operations had allowed starting of corrosion.

Therefore, for the structure concerned, and for future cases of similar assemblies, a number of modifications have been introduced. These modifications are directed firstly to improve the sealing between the parts to be assembled and secondly to improve the local protection after any machining operation accomplished for fitting purposes. No alterations have been introduced to the basic protective treatment of the components since this has been considered already satisfactory, but some changes on heat treatment process have been considered opportune and introduced.

The case shown at figure 3 is representative of extensive corrosion with deep cracks on a wing lower panel. Here corrosion started both around the fastener holes between wing panel and longeron as well as on areas of the panel free of holes. The initial corrosion was essentially of filiform type and developed successively into intergranular and exfoliating types.

The area concerned had been subjected, in the course of manufacture, to: shot peening, chromic acid anodizing, final painting of external surface with vinylic wash primer and acrilic finish.

The following changes have been introduced to correct the condition:

- Touch-up of concerned fastener holes with chemical oxydation;
- Wet assembly of fasteners;
- Application of a strontium chromate primer and acrilic finish;

The above treatment has been extended also to new productions with marked improvement of their corrosion resistance.

2.2. - Corrosion on structural attachments (wing, stabilizer, fuselage, etc.)

Stress-corrosion phenomena may occur on structural parts subjected to high loads when they are made of alloys with high mechanical properties but sensitive to stress-corrosion.

Insurgence of the phenomena may also be favored by concurrence of other factors such as presence of stresses above the threshold loads along the short transverse of the material, presence of stresses induced by incorrect assembly of the parts, etc. The two examples shown at figure 4 and 5, concerning a wing attachment and an horizontal stabilizer axle, have been corrected with design changes requiring for both of them replacement of the original Aluminium alloy 7079 T6 with 7075 T73.

For successive projects use of 7079 has been restricted for structural items sensitive to stress corrosion.

Also the fuselage lower parts, and in particular those incorporating landing gears and attachments thereto, are, because of their exposure to both humidity and abrading dust, particularly sensitive to corrosion which may develop on them, both as stress corrosion on the classical manner, as well as with different appearance (see figure 6.).

The case shown at figure 7 illustrates a failure due to crevice corrosion of a nose landing gear retraction actuator attachment.

While for the failure of the landing gear attachment at figure 6 the correction proposed was to replace the original 2014 Aluminium alloy with 7075 T73 Aluminium alloy, for the landing gear strut at figure 7, which is made from a forging in 4340 high resistance steel, the crack started from corrosions, the development of which was favored by the presence of the unmachined surface on the area subjected to high pulsating loads.

It was therefore decided to machine finish all surfaces of the landing gear strut. The same treatment was applied to other parts made of similar high resistance steel even where no mechanical coupling is to be made. Shot peening has been required in all cases after machining.

The case shown in simplified manner at figure 8 is presented as a significant example of failure due to stress corrosion occurred inside a landing gear strut made of 7079 T6 Al alloy.

The surface of the internal cavity of this strut, even if painted, was subjected to the action of atmospheric agents and, the occurrence of stress corrosion phenomena was favoured by the type of machining which was accomplished inside the strut after heat treatment, with resulting residual stresses being present.

The corrective action has therefore been mainly directed to eliminate such residual stresses through shot peening of the surface of the cavity, surface protection being then completed by chromic acid anodizing and painting with zinc chromate primer and epoxy finish.

2.3. - Other typical cases of corrosion

In addition to the primary structures quoted on the preceding examples, other aircraft parts may be affected by corrosion phenomena, which, even if less dangerous from a safety of flight standpoint, may entail considerable problems of repair and parts replacement and therefore increase the overall operating costs.

Some examples of such corrosions along with the technical corrective actions adopted are quoted hereafter:

- Air intakes and air intake ducts: surface pitt corrosion found. The problem has been solved painting all air intakes and air intake duct surfaces.
- Passenger, cargo and inspection doors outer rim: exfoliation and intergranular corrosion found. Wet assembly of bolts, nuts and rivets has been adopted, to improve water tightness around the rim area the profile elements have been assembled with interposition of sealant, adoption of improved surface protections and, where necessary, change of some material.
- Magnesium alloy estrusions on wing and control surfaces trailing edge: pitting and intergranular corrosion found. The suggested solution is to replace, whenever possible, the magnesium alloy extrusions with other extrusions made of Aluminium alloy or composite material.
- Magnesium alloy landing gear components: like the above mentioned extrusions, they are particularly sensitive to pitting and intergranular corrosion and must therefore be adequately protected, or better, be replaced with others made of Aluminium alloys.

- Battery bay areas: corrosions caused by electrolytic liquids found. Restoration of the required anti-acid paint and reccomendation to accomplish frequent washings of the bay to remove possible fluid deposits.
- Inside of fuselage lower areas: corrosions due to stagnation of moisture. Restoration of the original protections with an appropriate paint system and adoption of adequate drains.
- Gun bays: corrosions caused by firing exhaust found. As on battery bay cases, correction is accomplished restoring the original protection with an appropriate paint system and washing of the bay after each firing to assure removal of corrosive agents.
- Hydraulic and fuel system lines: corrosions found on the areas of contact between dissimilar metals, essentially fittings, nuts, fastening clamps, etc. The cure is to replace the corroded parts and to introduce appropriate intermediate materials whenever possible.
- Components of hydraulic and electrical actuators: galvanic oxydations and corrosions found. Corrective actions in these cases consist on accurate cleaning and successive application of protective oil.
- Antennas: exfoliation corrosions found. Correction is accomplished applying a chromic acid anodizing followed by application of an appropriate paint system.

2.4. - Particular cases of corrosion on highly stressed bolts and pins

The example shown at figure 9 concerns a space application requiring structural connection through a conical pin made of Inconel 718 and a Titanium lug. This case was discovered during an inspection accomplished after a fatigue test.

The examination under a 25 x microscope has evidenced extensive areas of abrasion with micro-cracks both on the pin and on the corresponding seat on the lug due to fretting corrosion; the early formation of oxyde dust between the surfaces in contact has contributed to spread the abrasion.

The phenomena has occured in spite of the extreme accuracy of the surface finish for both pin and hole and the very tight coupling tolerance and has therefore been attributed to the contact between two dissimilar materials, without intermediary and in presence of heavy loads.

Since the case concerns space hardwares the adoption of conventional antifretting organic compounds has not been possible because of their high rate of outgassing. Correction has been effected silver plating the pin.

2.5. - Corrosions on bonded honeycomb sandwich structures.

We have seen, from record about protections not completely efficient throughout the aircraft life time, that valuable information may be gathered to improve or resolve problems on corrosion prevention of typical aircraft structures. We would like to present now a case where the original protection proved highly successful.

The first metallic honeycomb structures made by Aeritalia for production aircraft were the elevators for the G91 light fighter and its derivations, the design of which dates back to the years 1959÷1960.

At the time the fear of corrosions, caused by humidity infiltrations inside the honeycomb cells, was one of the most serious elements holding back extensive adoption of honeycomb bonded structures.

To allow evacuation of the gases developed during the adhesives polymerization, the honeycomb cells were then provided with ventilating holes, the presence of which allowed passage of humidity during service.

Having ascertained the low efficacy of the surface protective treatments on the honeycomb available at that time, it was decided to try to achieve, for the elevator concerned, an airtight seal, to be verified with a pressure test during manufacture. Complete sealing was to be made only after prolonged purging with dry nitrogen of the stabilizer inner areas.

The above described technique, resulting from a rational design approach, has allowed production of hundreds of stabilizers which resulted free from corrosion on the honeycomb even after 20 years of service. The airtight sealing design was successfully introduced also on the wings of a ground to air missile which were of sandwich type with metallic honeycomb core.

The wings incorporating the new design feature were free from corrosion (on the honeycomb) even when exposed to weather during their long periods of stay on the firing ramps.

In general the honeycomb sandwich structures have, for years, constituted a real problem from the point of view of corrosion prevention.

Considerable progress has been achieved with the adoption of non-perforated honeycomb, or of honeycomb protected with an adequate surface treatment (based on the spraying of fluid elastomers) coupled with the introduction of adhesives which, because of their reduced sponginess, do not transmit humidity toward the inside. In addition, the chemical formulation of such adhesives has been improved to make them inert after polymerization and avoid corrosion of chemical type to the honeycomb. Lastly the adoption of pre-bonding surface treatments such as phosphoric acid anodizing has further improved the resistance to corrosion properties of the honeycomb.

Today a satisfactory degree of corrosion resistance has been reached using, in addition to the above mentioned pre-bonding, special primers and adhesives developed for that purpose.

It is anyway always a safe rule, in our opinion, to build, whenever practical, a barrier to seal out external humidity.

3. PRESENT TREND FOR EFFECTIVE CORROSION PREVENTION

The integration of Aeritalia structure design manuals with the latest data on corrosion prevention is a continuous process, particularly for what the in-service behaviour of structures made of new material, both metallic and composite with a resin matrix, and with new manufacturing processes, is concerned.

This continuing up-dating of the structure design manual, is required to associate to each structural part of the aircraft the most suitable corrosion prevention treatment, as well as to enable planning of in-service inspection of the structures in accordance with the principle of maximum reliability without penalization of the vehicle with undue groundings for inspection.

Organization of the above activities, finalized to an effective prevention of corrosion, requires an ever increasing coordination of the efforts that have so far been individually developed by all Departments concerned such as Engineering, Manufacturing Research & Development, Manufacturing, In-Service Support, etc. An example of a possible type of such finalized organization is schematically shown at figures 10 and 11.

The validity of the work accomplished for prevention of corrosion, when based both on theoretical study of the phenomena as well as on the practical experience acquired with aircraft use, is confirmed by the development, by most of the major aircraft manufacturer, of numerous improvements incorporated on new design and on running production.

Some of the most significant improvements concerning metallic structures are:

a) Replacement of Aluminium alloys 7079 T6 & 7075 T6 with 7075 T73.

b) Protection of external surfaces exposed to corrosive agents with strontium chromate primer and high flexibility polyurethanic finish.

c) Replacement of Magnesium castings, when these are exposed to agents conducting to corrosion, with parts made of Aluminium alloy and, for the parts to be mantained in magnesium, adoption of special protections such as oven paint.

d) Use, on specific areas, of organic corrosion inhibitors.

e) Installation of non aluminium external fasteners with interposition of wet sealant or primer.

f) Surface pre-bonding preparation with phosphoric acid anodizing and corrosion inhibiting adhesive primer.

g) Use of sealants loaded with chromates.

h) Installation of bushings with interposition of primer and sealant.

i) On high resistance steels, accomplishment, whenever possible, of vacuum cadmium plating instead of the standard electrolytic plating.

j) Provision of drain valves or drain holes on all fuselage areas were moisture may accumulate.

k) Use of Al-clad external skins with highly shined surfaces.

l) Complete painting of parts prior to assembly and successive painting of the assembled structure.

In addition, the above measures have usually been implemented with some design and fabrication general rules such as:

- Avoid, for some types of semi-finished parts, too deep machining operations in order not to cut and expose the metal fibres with consequent negative effects on corrosion.
- Pay attention, during all manufacturing phases, such as machining, heat treatment, metal deformation, etc., to minimize, as much as possible, any residual built-in stress on the semi-finished item. Whenever there are reasons to believe the presence of residual tensile stresses within the item's surface layer, it is advisable to adequately relieve them before proceding with any surface treatment.
- For some type of semi-finished items the conditions of supply must be oriented to require pre-compressed or pre-stretched conditions to obtain finished items substantially free of strong internal stresses.
- Pay much attention, during the manufacturing process, to the temporary protection and cleanliness of the items.
- Make sure, through adequate engineering dispositions, that the material is not unduly stressed along the short transverse of the fibre.
- Avoid machining operation resulting in removal of the surface protection ; if the removal is not avoidable, reinstate the protection with a surface treatment at least as efficient as the original one.
- Adopt, whenever possible, the double protection criteria.

Also for the ever extended and important structural applications of advanced composite materials, such as carbon, glass and Kevlar fibers in resin matrix, appropriate surface protective treatments are required.

Notwithstanding the fact that those materials are free from corrosion phenomena as previously described, absortion of atmospheric moisture must be impeded because it might be the cause of lower mechanical properties and of micro cracks initiation. This being particularly felt when the humidity is associated with heat.

The whole subject is still under study and the stage of experimentation as well as the availability of in service behaviour data, being still relatively scarce, do not allow, for the time being, to refer experiences comparable to those accumulated for metallic structures.

In addition particular measures could also be required each time parts made of carbon fibre composites must be assembled with metallic parts, this to take care of the fact that carbon fibres being conductive, in presence of humidity, galvanic couples may take place with consequent possible corrosion of the metal.

The above case, like other is subject to research and experimentation to determine its real importance.

For both, metallic and resin base non metallic materials, with particular emphasis for these last ones, techniques to monitor corrosion phenomena or degradation of structural properties have been experimented or are being studied. These techniques are essentially based on the phenomena of acoustic emission to attempt to measure, both during periodic maintenance and during service, the presence of mechanical discontinuity in propagation within the structures.

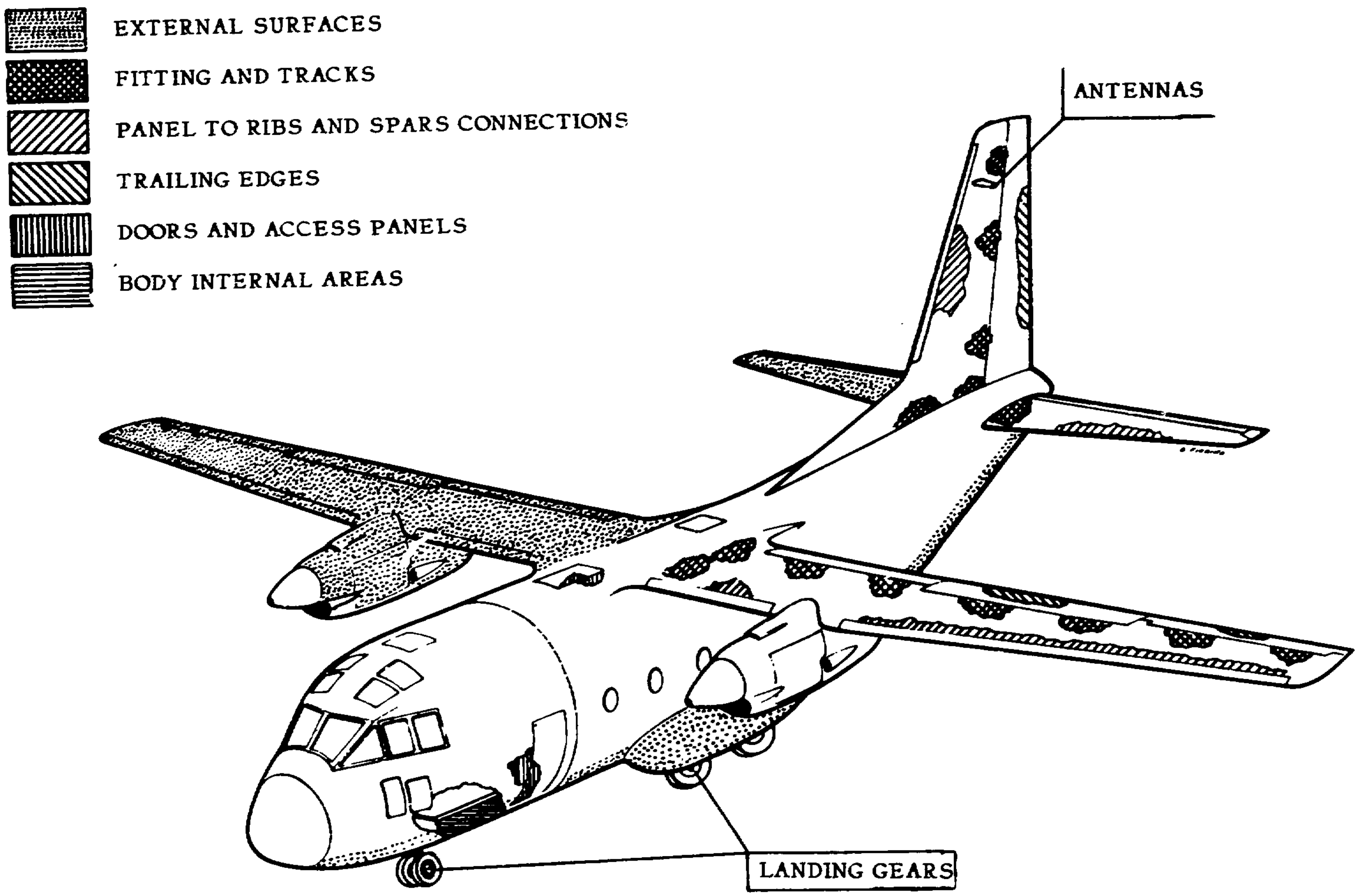


FIGURE 1. AIRCRAFT TYPICAL PARTS TO BE IMPROVED FOR CORROSION PREVENTION

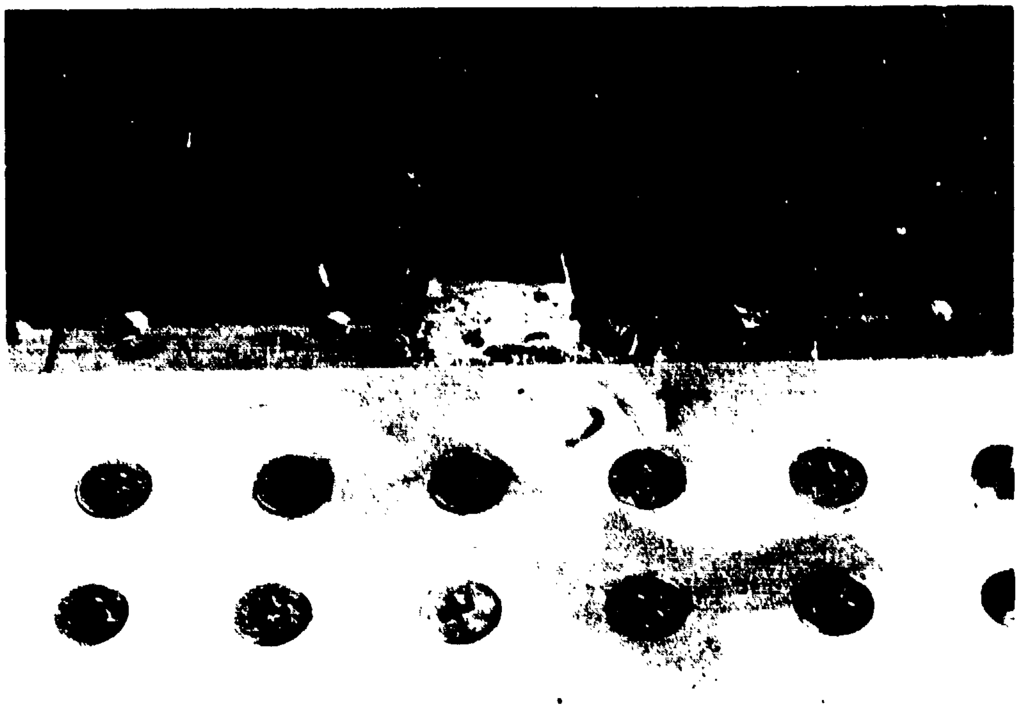


FIGURE 2. PROPAGATION THROUGH SUCCESSIVE LAYERS DUE TO CORROSION BY EXFOLIATION.

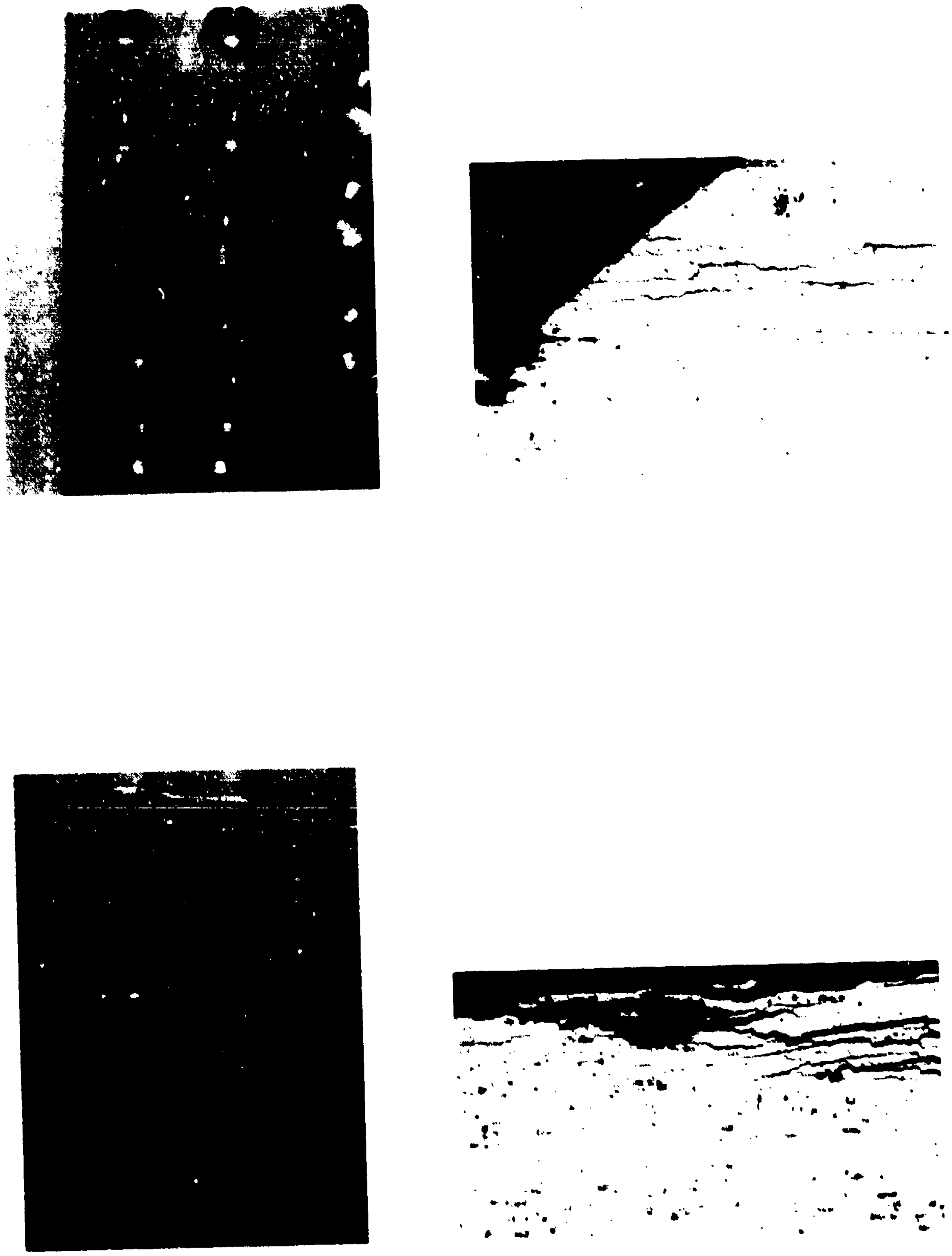


FIGURE 3. CORROSION BY EXFOLIATION WITH CRACKS THAT SUCCESSIVELY PROGRESSED FOR STRESS CORROSION.

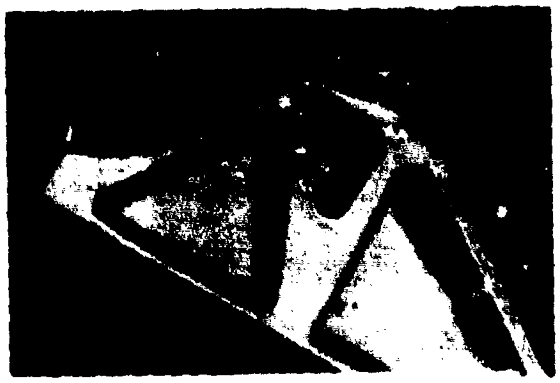


FIGURE 4. STRESS CORROSION ON A FITTING.

FIGURE 5. STRESS CORROSION ON A STABILIZER AXLE INTERNAL SURFACE.

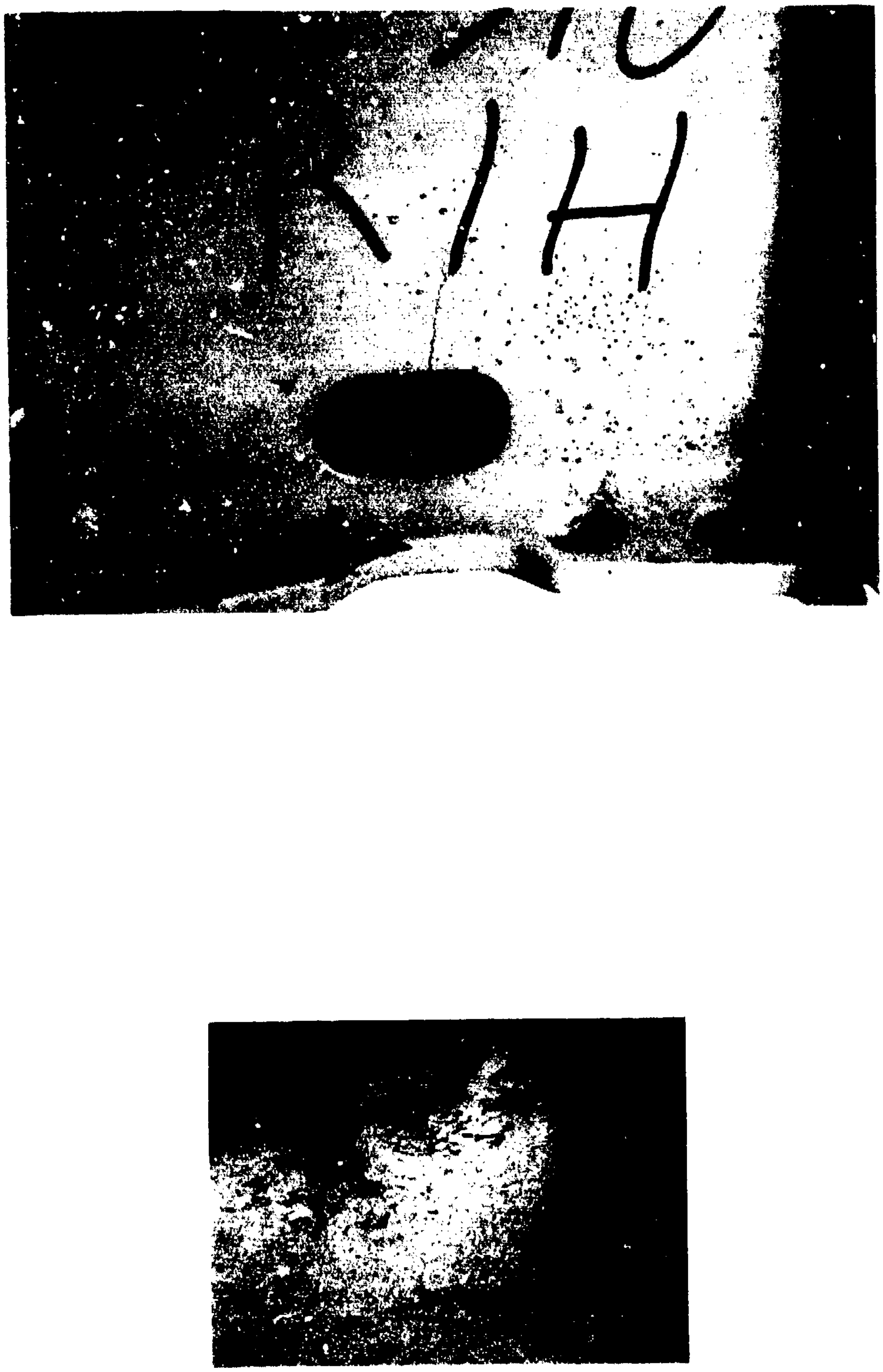


FIGURE 6. STRESS CORROSION ON A MAIN LANDING GEAR FITTING.

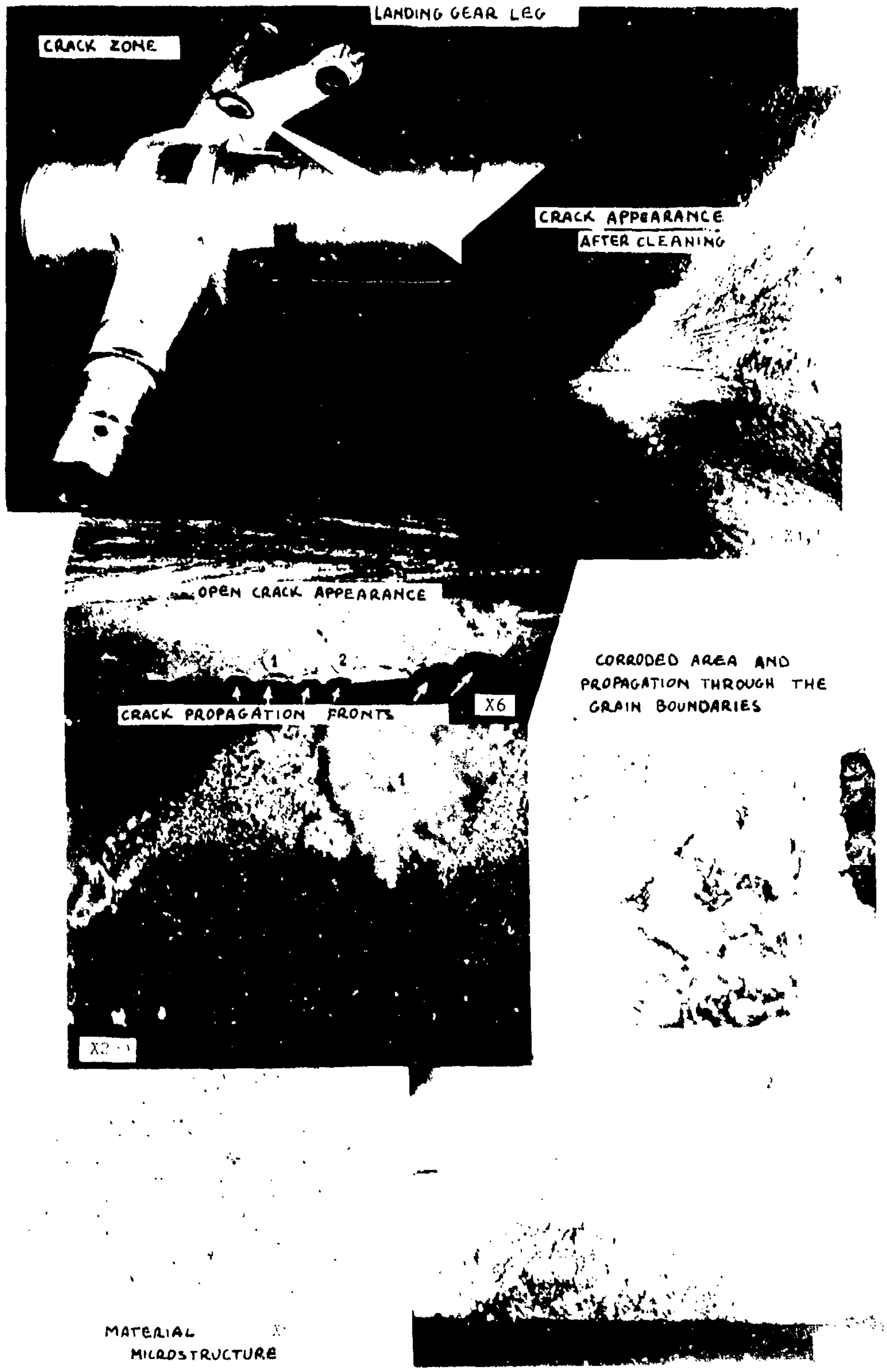


FIGURE 7. FAILURE ON THE ACTUATOR FITTING OF A NOSE LANDING GEAR.

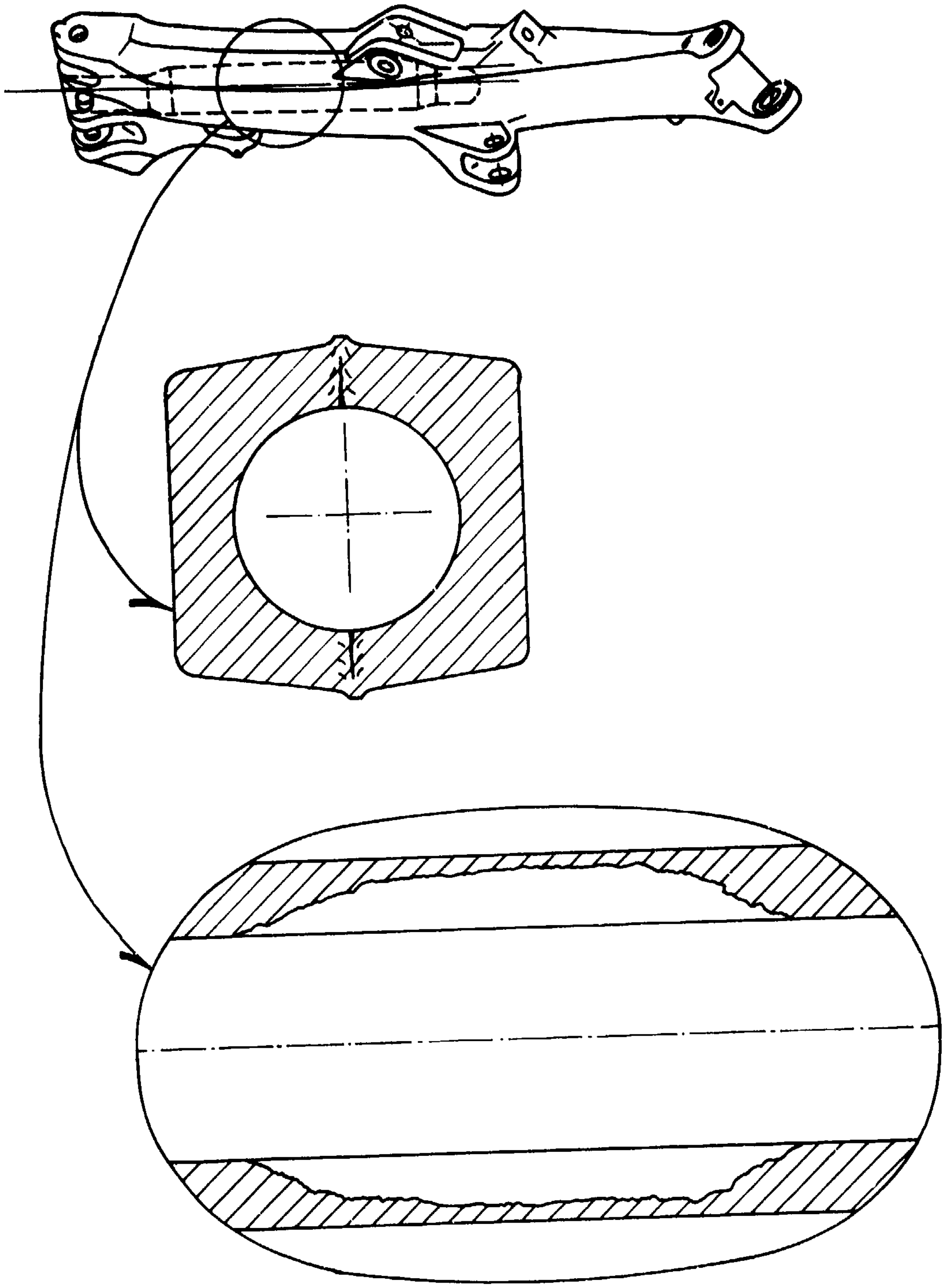


FIGURE 8. FAILURE DUE TO STRESS CORROSION ON A LANDING GEAR STRUT.

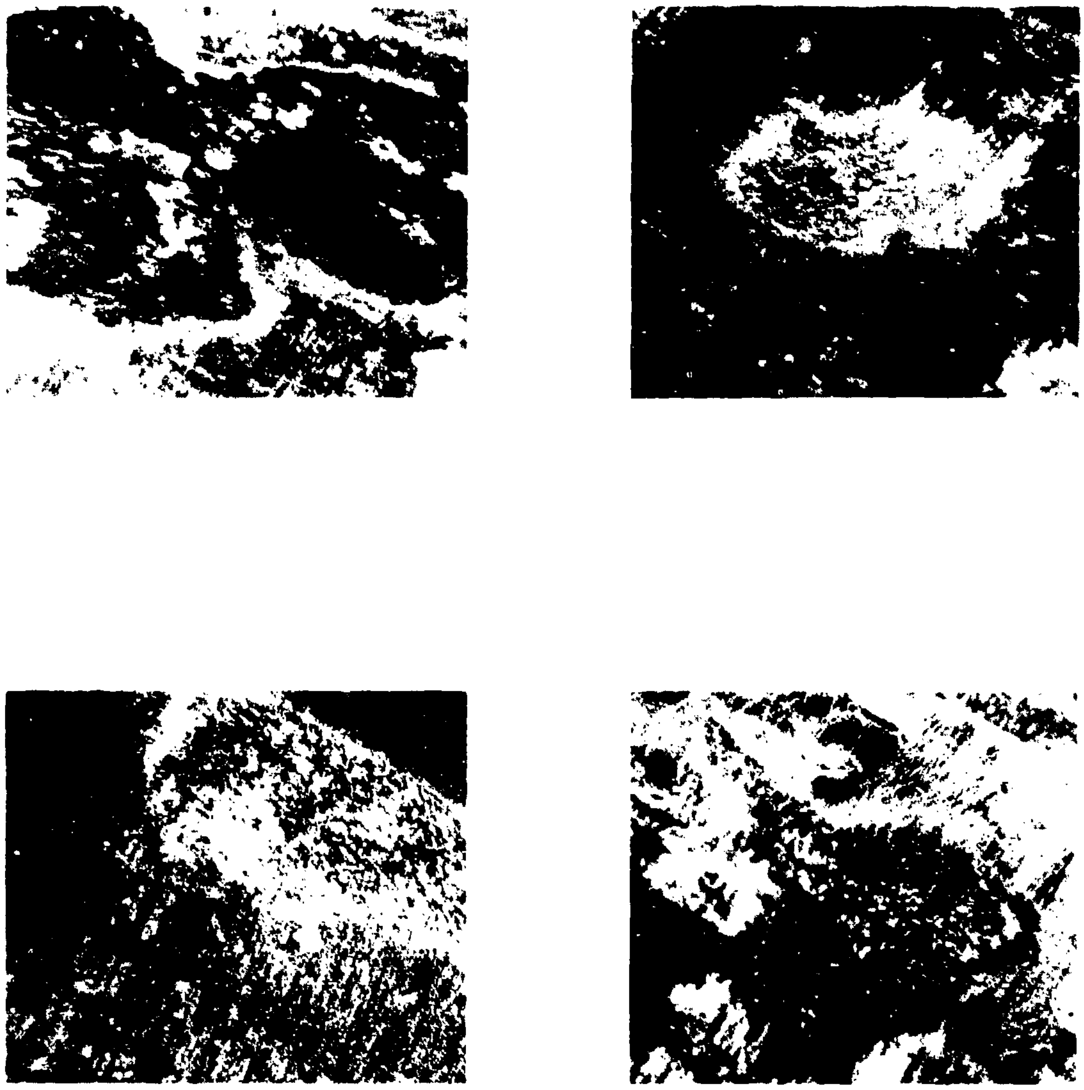


FIGURE 9. FRETTING CORROSION ON AN INCONEL PIN ON A TITANIUM HOUSING.

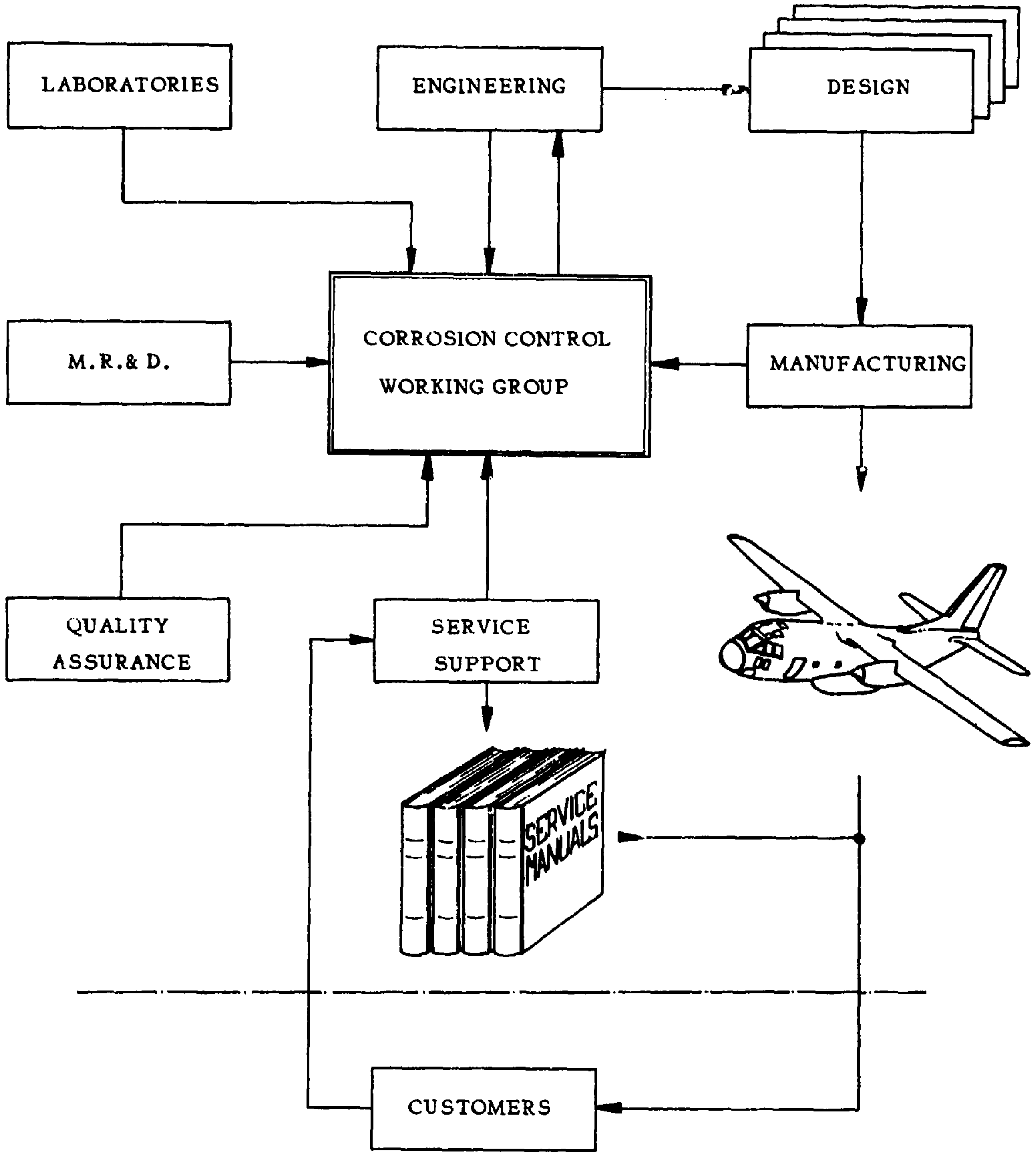


FIGURE 10. CORROSION PREVENTION INTEGRATED MANAGEMENT

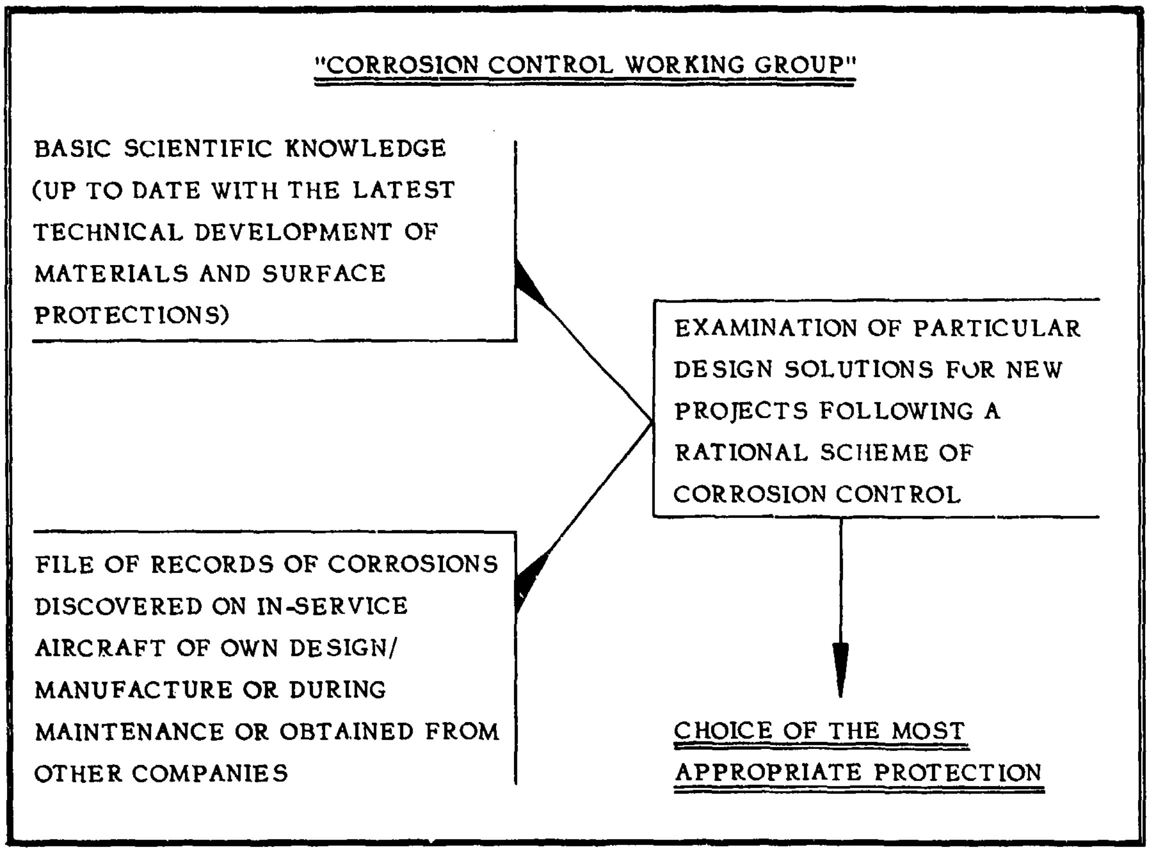


FIGURE 11. EXAMPLE OF MODE OF OPERATION OF CORROSION CONTROL WORKING GROUP.

SOLUTIONS PREVENTIVES UTILISEES CONTRE LA CORROSION LORS DE LA CONSTRUCTION D'UNE CELLULE D'AVION

CAS DES ALLIAGES 2014 ET 2214

Par J. BEVALOT
AVIONS MARCEL DASSAULT - BREGUET-AVIATION

1 - INTRODUCTION.

La lutte contre la corrosion doit intervenir à tous les stades de la conception et de la réalisation d'une cellule d'avion.

. Dessin des pièces.
. Choix des matériaux et des traitements thermiques.
. Technologie d'assemblage et de liaison.
. Gamme de protection.

La norme Française AIR 7251 spécifie bien les divers paramètres à prendre en considération lors de la conception et de la réalisation d'une cellule d'avion.

Par corrosion, il faut comprendre l'ensemble des dégradations que peut subir la structure de l'avion hormis les effets mécaniques bien que ces derniers interfèrent avec les agents physico-chimiques.

La corrosion peut prendre divers types :

. Généralisée.
. Galvanique.
. Microbienne.
. Intercristalline.
. Sous tension.................

La corrosion est nuisible du point de vue aspect mais souvent elle est très dangereuse car elle peut être le siège d'initiation de fissures de fatigue ou provoquer des ruptures soudaines et imprévisibles (corrosion sous tension).

Les avions sont appelés à avoir des longévités de plus en plus grandes et des durées de vie élevées.

La maintenance prend donc une importance considérable et tout doit être mis en oeuvre pour réduire les coûts des réparations des dégats causés par la corrosion.

2 - GENERALITES SUR LA LUTTE CONTRE LA CORROSION.

A - Lors de la conception et du dessin des divers éléments de la structure, il faut rechercher les solutions évitant les phénomènes de condensation, de ruissellement et de rétention d'eau ou plus généralement de liquides de toutes sortes. Dans la mesure du possible, éviter le confinement.

Par ailleurs, on ne parlera pas ici de la corrosion microbienne qui se produit dans les réservoirs structuraux contenant du Kérosène en présence d'eau et d'oxyde de fer. Ce type de corrosion est en général évité maintenant par des drainages de l'eau et la présence d'orifice de vidange dans les points bas ainsi que l'emploi de vernis (type polyuréthane) étanches et compatibles avec les produits d'étanchéité.

B - Le choix des matériaux et de leur traitement thermique est aussi très important.

Le matériau retenu pour un type de pièce donné est le résultat d'une analyse faisant intervenir le problème des caractéristiques statiques, éventuellement celui de la résistance à l'initiation des criques de fatigue, celui de la résistance à la propagation de ces dernières..... et enfin de la résistance à la corrosion.

De cet ensemble, se dégage un compromis qui ne conduit pas forcément à l'optimisation du paramètre corrosion . En particulier, les alliages à haute résistance de la famille aluminium cuivre, choisis pour leur bonne résistance à l'initiation en fatigue alliée à des caractéristiques statiques confortables, présentent certaines faiblesses dans le sens travers-court vis à vis de la corrosion sous tension.

Du coté choix des matériaux, il faut aussi prendre en considération également les problèmes de corrosion galvanique. Il faut éviter que le phénomène de pile puisse apparaître et pour cela on évitera la présence d'humidité (électrolyte) et on interposera un isolant entre les matériaux dissemblables (mastinox par exemple) ainsi il n'y aura pas de contact possible.

Par ailleurs, du point de vue matériaux, le choix du type de demi-produit et son mode d'élaboration :

. Laminé.
. Forgé.
. Tractionné.
. Comprimé.

influeront également sur la résistance à la corrosion sous tension par élimination partielle ou totale du travers court. Mais dans ce choix intervient aussi le prix de revient et pour cette raison malheureusement ce n'est pas toujours le meilleur demi-produit qui est choisi.

Le traitement thermique peut être aussi ajusté pour optimiser la résistance à la corrosion sous tension. Mais, très souvent, la meilleure résistance à la C.S.T. n'est pas compatible avec les autres caractéristiques et là aussi un compromis est nécessaire.

C - La technologie de réalisation des pièces et des assemblages devra donc permettre en quelque sorte de récupérer ce que les compromis précédents auront fait perdre.

D - La gamme finale de protection de l'ensemble de la cellule devra en dernier lieu retarder au maximum l'apparition des dégradations aussi minimales soient elles.

Maintenant, nous allons illustrer les précédents propos avec les alliages 2014 et 2214.

3 - SOLUTIONS TECHNOLOGIQUES ET METALLURGIQUES POUR MINIMISER LA CORROSION SOUS TENSION DU 2214.

Le 2214 à l'état normal d'utilisation (caractéristiques mécaniques optimum) est très sensible au phénomène de corrosion sous tension ; en effet, il ne peut admettre de contraintes permanentes dans le travers court supérieures à 70 MPa (soit environ 20 % R 0,2).

Un certain nombre d'essais ont été effectués afin de déterminer les solutions technologiques ou purement métallurgiques qui minimisent les risques de corrosion sous tension et définir ainsi :

. Une technologie de pose des fixations dans le travers court des tôles épaisses.
. Une gamme de protection.

En parallèle à ces études, nous avons étudié un traitement thermique de léger sur-revenu pour une désensibilisation de l'alliage mais ce dernier est souvent abandonné en raison des chutes de caractéristiques mécaniques induites.

De même, nous avons étudié l'influence des matricés vis à vis de la C.S.T. par élimination du sens travers court.

3.1 - Paramètres d'assemblage.

3.1.1 - Définition des essais.

Les essais ont été réalisés sur plaquettes assemblées par rivets avec douilles serties ou vis tête H. Ils ont permis l'étude des paramètres suivants (les éléments de fixation avaient pour diamètre 8 et 10 mm) :

. Interférence (serrage 10 μm, 20 μm, 30 μm ou jeu 7 μm).
. Finition des alésages et des surfaces.
. Conditions de traitement thermique (température de revenu).
. La gamme de finition (peinture).
. Interposition de produit d'étanchéité au montage.

Les éprouvettes sont conformes à la définition de la planche N° 1. Les éprouvettes sont constituées par l'assemblage de plaquettes prélevées dans le sens travers court. L'interférence de montage de l'élément de fixation induisant des contraintes dans la zone travers court, la définition des gammes complètes de ces éprouvettes est donnée par le tableau de la planche N° 2 sur lequel figurent aussi les résultats d'essais, nous y reviendrons plus tard.

Les essais ont été réalisés en corrosion sous tension en immersion-émersion alternée (10 minutes - 50 minutes) dans une solution A_3 d'eau de mer artificielle pendant une durée de 2 mois.

Les contraintes sont introduites :

. Par le montage avec serrage des fixations dans leur alésage.
. Par le galetage des angles vifs des alésages qui entraînent des contraintes circonférentielles de traction.

La planche N° 3 donne l'évolution des contraintes circonférentielles en fonction du diamètre pour un élément en titane avec une interférence de 10 microns.

3.1.2 - Résultats des essais.

Après essais, toutes les éprouvettes sont désassemblées. On constate que la corrosion par piqûres est importante sur les plaques extérieures mais qu'aucune crique n'est visible. Suite à cela, les éprouvettes sont plongées dans un bain décapant de façon à mettre le métal à nu.

Puis on procède à une inspection des alésages ce qui permet de déceler quelques criques. Pour un examen plus approfondi, toutes les éprouvettes sont soumises à un essai de ressuage rouge.

Les résultats obtenus sont portés sur la planche N° 2.

. Examen micrographique.

Un examen micrographique a été effectué sur chaque éprouvette (soit à l'endroit où l'examen visuel après ressuage avait permis de détecter une crique soit au hasard sur les autres).

Les différents clichés confirment bien que l'on est en présence du phénomène de corrosion sous tension.

Le premier enseignement est qu'en absence de compression pure en bordure d'alésage, la fissuration par corrosion à caractère intergranulaire se développe d'où l'intérêt de cette opération au bord de l'alésage.

Par ailleurs, la protection apportée par le produit d'étanchéité est également remarquable.

3.1.3 - Exploitation.

L'ensemble des résultats d'essais permet de tracer les diagrammes (travers court de produits laminés) de la planche N° 4.

Ainsi, il est pallié au manque relatif de résistance à la corrosion sous contrainte du 2214, par des gammes spéciales de fabrication dont voici un aperçu :

. Gamme de pose des éléments de fixation :

- Perçage des avant trous.
- Compression de surface par sablage humide.
- Oxydation anodique chromique (protection de base).
- Finition des alésages (brochage).
- Cassage d'angle 0,2 à 0,3 mm à 45°.
- Pour les gros diamètres, opération de sablage à sec.
- Peinture impression phosphatante.
- Cas des assemblages non étanches.
  Montage avec interposition sous tête de produit d'étanchéité.
- Cas des assemblages étanches à l'air et au kérosène.
  Montage avec produit d'étanchéité sous tête complété par une interposition entre les pièces.

Malgré ces précautions, dans certains cas critiques (très hautes contraintes dans le travers court), le 2214 est remplacé par le 2618 A réputé moins sensible envers ce phénomène.

Par ailleurs, cette gamme peut être encore améliorée par un léger sur-revenu dont nous parlerons plus loin.

Notons enfin que le passage aux produits matricés permettra d'augmenter encore le seuil d'apparition de la corrosion sous contrainte. C'est ce que nous allons voir maintenant.

3.2 - Influence du demi-produit d'origine.

3.2.1 - Définition des essais.

. Prélèvement dans le matricé.

Un type spécial d'éprouvette a été choisi afin de permettre le prélèvement dans une pièce matricée en laissant subsister les surfaces extérieures dans l'état où elles se trouveront sur avion.

L'éprouvette ainsi définie a la forme d'une équerre conformément à la planche N° 5 qui reproduit également le schéma de prélèvement.

. **Prélèvement dans les tôles épaisses.**

Des éprouvettes cylindriques classiques de ∅ 4 mm sont prélevées dans le sens travers court d'une tôle d'épaisseur équivalente à la hauteur du matricé.

Afin de pouvoir comparer directement les résultats d'essais de corrosion sous tension, obtenus sur les équerres du profilé matricé, avec ceux obtenus sur tôles épaisses, il est usiné dans celles-ci des équerres définies précédemment prélevées de manière à respecter l'orientation donnée sur le schéma de la planche 6.

3 types de revenus ont été appliqués :

. 22 heures à 160°C sur les matricés comprimés.

Sur tôle épaisse {
. 24 heures à 153°C revenu donnant les caractéristiques optima.
. 24 heures à 178°C revenu donnant la meilleure résistance à la C.S.T. de l'alliage.

3.2.2 - **Conditions d'essais.**

. **Mode de sollicitation.**

Toutes les éprouvettes (cylindriques ou équerres) ont été sollicitées en flexion par l'intermédiaire d'un bras de levier. Le schéma de la planche 7 donne le dispositif d'essais.

. **Cycle de corrosion.**

Les essais ont été effectués en immersion-émersion alternée (10 mn - 50 mn) dans une solution A_3 renouvelée chaque semaine.

Toutes les éprouvettes ont subi avant l'essai un décapage fluonitrique et une neutralisation.

Les éprouvettes non rompues sont démontées au bout de 30 jours.

Dans le cas d'éprouvettes cylindriques, celles-ci sont alors soumises à un essai de traction afin de déterminer leur résistance résiduelle.

Par ailleurs, des eprouvettes sont laissées sans contrainte dans les mêmes conditions afin de déterminer la part de la corrosion généralisée vis à vis de la fissuration sous contrainte dans la chute de la charge de rupture.

Résultats.

L'ensemble des résultats a permis de tracer les courbes de la planche 8 . L'examen des résultats montre que :

. La limite de non rupture pour le traitement de revenu normal (24 heures à 153°C) est très basse (quel que soit le type d'éprouvette). Elle est de l'ordre de 8 hbars soit environ 19 % de la limite élastique à 0,2 %.

. Pour le traitement expérimental 24 heures à 178°C, la limite de non rupture est supérieure à celle du traitement à 153°C à savoir :

. Eprouvettes cylindriques : 15 hbars
soit 38 % de R 0,2.

. Eprouvettes équerres : 19 hbars
soit 48 % de R 0,2.

. Sur les équerres A et B, prélevées dans les ailes longitudinales du matricé, aucune rupture ne s'est produite pour une contrainte inférieure ou égale à 26 hbars.

. Les équerres C se sont rompues pour des temps relativement courts jusqu'à 25 hbars. Il semble donc que les équerres prélevées sur l'aile transversale aient un fibrage plus défavorable vis à vis de la corrosion sous tension.

. Des essais complémentaires ont été entrepris sur les tôles pour chiffrer l'influence du revenu sur les caractéristiques mécaniques statiques et sur la résistance à la propagation des fissures. Les résultats sont portés sur les courbes de la planche 9 pour les résultats de traction et sur la planche 10 en ce qui concerne l'énergie de rupture après fissuration.

Conditions de revenu	R (hbar)	R 0,2 (hbar)	A %
24 heures à 153°C	48,3	44,6	11,6
24 heures à 178°C	46,7	42,5	10,6

On peut donc dire que le revenu de 24 heures à 178°C par rapport au revenu de 24 heures à 153°C :

a) - Fait chuter les caractéristiques mécaniques :

- de 2 hbars sur la limite élastique.
- de 1,5 hbar sur la charge de rupture

les allongements restant constants.

b) - Donne des énergies de rupture après fissuration, équivalentes.

3.3 - Conclusion.

L'étude comparative menée en corrosion sous tension sur tôles épaisses et bloc matricé a montré que :

. Sur tôles épaisses.

. Après un revenu de 24 heures à 153°C , la limite de non rupture en corrosion sous tension peut être prise égale à 70 MPa.

. Après un revenu de 24 heures à 178°C , la limite de non rupture est sensiblement relevée (de l'ordre de 150 MPa).

. Les essais effectués sur les équerres ont donné des résultats sensiblement équivalents.

Les équerres prélevées dans la tôle traitée à 178°C donnent une limite de 190 MPa.

. Sur produits matricés.

Toutes les équerres prélevées par comparaison dans une pièce matricée traitée 22 heures à 160°C ont donné des résultats supérieurs.

Cette amélioration n'est pas le fait du traitement thermique qui théoriquement devrait donner des résultats intermédiaires entre les courbes tracées pour les revenus de 178°C et 153°C (sur tôles épaisses).

L'amélioration est due à la texture du matricé, en effet sur les différentes équerres examinées, le sens du fibrage n'est jamais perpendiculaire au sens de l'effort.

Les essais ont montré que les produits matricés sont moins sensibles à la corrosion sous tension que les tôles épaisses et que le traitement de revenu de 24 heures à 178°C conduit à une amélioration de la tenue de l'alliage en corrosion sous tension mais en revanche entraîne une légère chute des caractéristiques statiques.

3.4 - Les traitements de surface.

C'est le problème de la santé de la peau d'une pièce

Cette qualité de la peau comprend :

a) - Son état de surface, c'est-à-dire sa rugosité qui conditionne la résistance à la fatigue.

b) - L'existence de contraintes résiduelles de surface qui vont favoriser ou retarder les phénomènes de fatigue et de corrosion.

c) - L'inhibition de cette surface vis à vis des agents extérieurs, contre la corrosion.

Dans la société AMD-BA , la solution la plus couramment utilisée sur les pièces en alliages légers est une oxydation anodique chromique précédée d'une compression de surface.

La compression de surface est obtenue par projection de billes de verre sur les surfaces ou par galetage ou coïnage sur les arêtes.

3.3.1 - Compression de surface des alliages légers.

La tenue en corrosion sous tension et la résistance à la fatigue de matériaux tels que le 2014 à l'état revenu (T6) ou le 2024 à l'état trempé mûri (T3) peuvent être améliorées par une compression de surface.

Nous différencierons les surfaces et les arêtes.

A - Traitements des arêtes.

Jusqu'à présent, le galetage était utilisé pour le traitement des bords des trous dans les assemblages mais ce procédé était loin de donner entière satisfaction.

Comme le montre la figure 1 de la planche 11 l'opération d'enfoncement et de rotation induit par adhérence une déformation plastique circonférentielle superposée à la déformation axiale de compression. Cette déformation plastique circonférentielle provoque des contraintes internes de traction nuisibles en regard des effets recherchés. Seules les contraintes de compression axiales sont intéressantes. Le croquis de droite sur cette même planche montre le principe de l'opération de coïnage vis à vis de l'opération de galetage.

Le coïnage est une compression par chocs matant l'arête à traiter sans déplacement relatif de l'outil vis à vis du matériau de la pièce en traitement.

Elle peut également être réalisée à l'aide d'un appareil à river monofrappe transformé. Dans ce cas, une opération reproductible est possible après règlage.

L'outil comporte une tête avec un arrondi bien calibré et un téton pilote. Un outil est nécessaire par diamètre.

Des essais , effectués en immersion-émersion alternée, ont vérifié l'avantage de la compression pure vis à vis de la compression effectuée avec rotation.

L'opération de coïnage peut également être remplacée par une projection à sec de microbilles de verre sur la bordure de l'alésage, ce dernier étant protégé par un tampon en caoutchouc. Les microbilles sont réaspirées par un tube concentrique à la buse c'est ce que l'on appelle le jet blast représenté sur la planche N° 12.

La planche 13 montre les résultats de fatigue obtenus sur des éprouvettes plates en 2014 formées de 2 demi-éprouvettes réunies par 8 vis et sollicitées en traction alternée P à 0,1 P pour un P maximal de 80 MPa ; on y voit la moyenne des cycles obtenus et l'écart type pour les divers essais.

On se rend compte que la compression du bord des alésages par coïnage ou par jet-blast donne les plus hautes valeurs.

Par rapport au galetage, on peut considérer que le coïnage augmente la durée de vie d'une puissance de 10.

B - Traitement mécanique des surfaces par sablage en voie humide.

Ce traitement mécanique de surface en voie humide, que nous appelons T.M.S.H., a pour double effet de ragréer et de décontaminer la surface ainsi que d'induire les contraintes de compression qui feront barrière à la corrosion et augmenteront la longévité en fatigue.

Un mélange d'abrasif et de billes de verre appelé SUPERBLAST permet la réalisation en une seule opération du ragréage et de la compression de surface.

Le SUPERBLAST a une granulomètrie de 90 à 170 microns et la concentration du mélange dans l'eau est d'environ 40 % en volume.

Les conditions opératoires sur pièces sont déterminées à l'aide d'éprouvettes de dimensions identiques à l'éprouvette ALMEN A2 (épaisseur = 1,3 mm) réalisée dans le matériau de la pièce à traiter avec une corrélation sur l'éprouvette ALMEN N_2 (épaisseur = 0,8 mm) en acier qui servira alors ultérieurement de contrôle.

1°) - Effet de ragréage.

L'opération de T.M.S.H. avec le SUPERBLAST S donne une rugosité de surface de Ra = 3,5 microns moyenne maximale lorsque l'on traite une surface de faible rugosité initiale.

Par contre, si l'on part d'un état de surface plus grossier (fraisage à grande avance) de l'ordre de Ra = 8 microns, cette rugosité est adoucie et devient de l'ordre de Ra = 5 microns.

En particulier, l'essai suivant a été réalisé : des éprouvettes de fatigue sollicitées en flexion plane ont reçu en leur partie centrale et sur chaque face une rayure transversale en V de 1/10 mm de profondeur pratiquée à l'aide d'un outil coupant avec enlèvement d'un copeau.

Cette série d'éprouvettes a été essayée à une contrainte de 19 hb comparativement à une série d'éprouvettes "référence" et à une série d'éprouvettes traitées au T.M.S.H.

Les résultats obtenus sont les suivants (valeurs médianes sur droite de Henry) :

Eprouvettes "Référence" usinées à Ra =	4,9 microns :	1,35 10^6 cycles
avec entaille	:	0,14 10^6 cycles
Entaille + Opération de TMSH	:	1,52 10^6 cycles

Ce qui montre que le traitement au SUPERBLAST annule l'effet néfaste sur la fatigue de la présence d'une rayure. On peut penser qu'il y a combinaison de 2 effets :

. Ragréage de la rayure par l'abrasif
. Diminution du facteur de concentration de contrainte et compression sur les bords de la rayure.

2°) - Action sur la fatigue.

Tous les essais ont été effectués en flexion alternée sur éprouvettes plates d'épaisseur 4 mm prélevées dans le sens travers long et en surface de tôles épaisses en 2014 de 60 mm d'épaisseur ou en 2024 ; dimension représentative des tôles d'où sont issus nos principaux panneaux intégraux.

La première série d'essais fut l'évaluation de la résistance à la fatigue en fonction des flèches ALMEN N_2 obtenues. On se rend donc compte que l'accroissement d'endurance est vite réalisé et que l'on arrive rapidement à la valeur asymptotique, c'est ce qu'expriment les figures 14 et 15.

Ensuite, la planche 16 concerne le 2014 état T 351 (tractionné à 2 %, non revenu) usiné, avec un état de surface de Ra = 1,6 à 3,2 microns. Sur la planche 17 figurent les résultats des mêmes essais à l'état T 651.

Après l'opération de compression-ragréage de surface, sur cette surface avivée, on pratique en première protection et directement après une oxydation anodique chromique sur les précédents graphes . On voit que l'oxydation anodique chromique entraîne une baisse de résistance à la fatigue, que le T.M.S.H. procure une augmentation d'endurance en fatigue de l'ordre de 20 % et enfin que le T.M.S.H. effectué avant oxydation annule la baisse initialement enregistrée et ramène la résistance à la fatigue à celle d'un état usiné suivi de compression par SUPERLAST.

Les planches 18 et 19 montrent les mêmes courbes de Wöhler que celles des planches précédentes mais concernent des éprouvettes usinées avec un état de surface Ra = 3,2 à 6,3 microns.

Ces résultats sont identiques.

Sur un matériau qui est "MOU" et dans la plage de rugosité considérée, l'effet de T.M.S.H. est le même.

La baisse de résistance à la fatigue due à l'oxydation anodique chromique est d'autant plus accentuée que la rugosité est grande.

L'augmentation de la résistance à la fatigue apportée par le T.M.S.H. avec le SUPERBLAST est de même importance sur état T 351 ou sur état T 651. Le T.M.S.H. annule la baisse due à l'oxydation anodique chromique et surtout l'influence de l'état de surface grossier en procurant une augmentation d'endurance en fatigue de l'ordre de 25 % sur l'état usiné à Ra = 1,6/3,2 microns protégé par une oxydation anodique chromique.

De plus sur les planches 17 et 19 nous avons tracé une courbe de Wöhler relative à un état de surface grenaillé à la bille d'acier ∅ 5/10 (conditions de grenaillage définies pour donner une hauteur d'arc de 20/100 mm sur éprouvette ALMEN A_2), suivi de T.M.S.H. pour décontaminer l'alliage léger d'éventuelles particules ferreuses, le tout suivi d'une oxydation anodique chromique On voit qu'en partant aussi bien d'un usinage à Ra = 1,6 à 3,2 microns ou 3,2 à 6,4 microns le grenaillage n'apporte pas d'amélioration sensible.

Des essais de C.S.T. ont également été menés sur :

. Brut d'usinage.
. Usinage + T.M.S.H.
. Usinage + T.M.S.H. + Oxydation anodique chromique.

Les résultats sont consignés dans la planche 20.

Comme nous l'avons déjà vu, à l'état non protégé, le 2014 est sensible à la corrosion sous tension, la limite de non rupture est très basse.

Elle est de 6 hbars pour l'état T 351, 8 hbars pour l'état T 651, ce qui s'explique par la limite élastique plus élevée de cet état. En % de E 0,2, cette limite de non rupture n'est que de 20 % pour les deux états. Après traitement au SUPERBLAST S, la limite de non rupture est nettement déplacée vers les contraintes élevées , elle se situe à 50 à 52 % de E 0,2, elle est donc 2,5 fois plus élevée qu'à l'état nu.

D'après la forme des courbes, on peut penser que l'effet de compression du SUPERBLAST retarde l'initiation de la crique mais il n'agit pas sur la vitesse de propagation.

Enfin, avec une protection anodique chromique superposée au SUPERBLAST, la limite de non rupture s'élève à 83 % de E 0,2.

On peut donc dire que ce double traitement immunise pratiquement le 2014 (tenue supérieure à 30 jours pour contrainte de 0,8 de E 0,2).

3°) - Résultats.

Le traitement de T.M.S.H. avec SUPERBLAST S :

1°) - Augmente l'endurance en fatigue du 2024 T 351 ou T 651 de 20 à 30 % suivant la rugosité de l'usinage.

2°) - Annule la baisse de résistance à la fatigue produite par l'oxydation anodique chromique.

3°) - Permet sur les pièces travaillant en fatigue d'accepter une rugosité d'usinage de 3,2 à 6,4 microns ce qui doit influer favorablement sur le prix de revient.

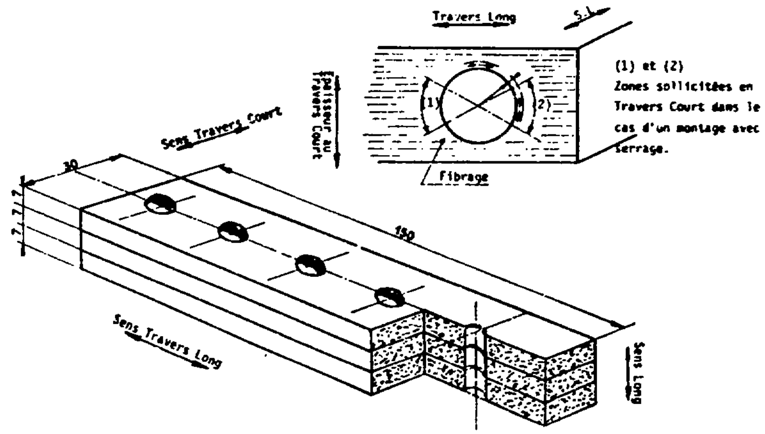
4°) - D'accepter de supprimer la compression de surface par grenaillage à la bille d'acier.

5°) - L'oxydation anodique chromique superposée au traitement T.M.S.H. immunise pratiquement le 2024 aux effets de la corrosion.

Ultérieurement, les surfaces seront peintes en 3 couches :

. Une couche d'impression phosphatante (8-10 microns)
. Une poste impression au chromate de zinc (15 à 20 microns).
. Une couche de finition (20 à 25 microns).

PLANCHE N° 1



EPROUVETTE POUR ESSAIS DE CORROSION SOUS TENSION

MATIÈRE : 2214 T 651 (24 HEURES À 153°C) -

PLANCHE N° 2

ESSAIS DE C.S.T. SUR PLAQUETTES EN 2214 ASSEMBLEES

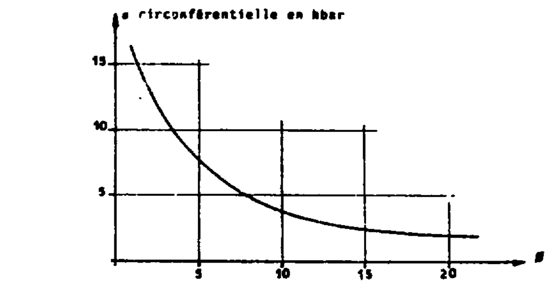
Séries / Opérations	Interférence 15 microns ø 10					Interférence 20 microns ø 10					
	1	2	3	4	5	A	B*	C	D*	E	F
Sunerblast (Compression de surface)	1	2	1	4	3	1	1	1	1	1	1
DI 4 Oxydation Anodique Chromique											2
Alesage (brochage)	2	1	2	1	1	2	2	2	2	2	4
Cassage d'angle			3	2	2			3	3	3	5
Galetage		4	3								6
Coïnage								4	4	4	
Peinture 1550 M											3
PR au montage										5	7
Observations	5 trous criqués / R.A.S.	R.A.S. / R.A.S.	4 trous criqués / 6 trous criqués	3 trous criqués / 4 trous criqués	2 trous criqués / 4 trous criqués	2 trous criqués	R.A.S. (1)	R.A.S. (1)	R.A.S.	R.A.S.	R.A.S.

Revenu 24 heures à 153°C Sauf séries B* et D* revenu 24 heures à 178°C

NOTA. Les criques sont situées sur les faces internes des plaquettes.

(1) Quelques petites criques ne touchant pas aux alésages ont été décelées sur l'interface, mais de faible profondeur, elles ont été éliminées au polissage.

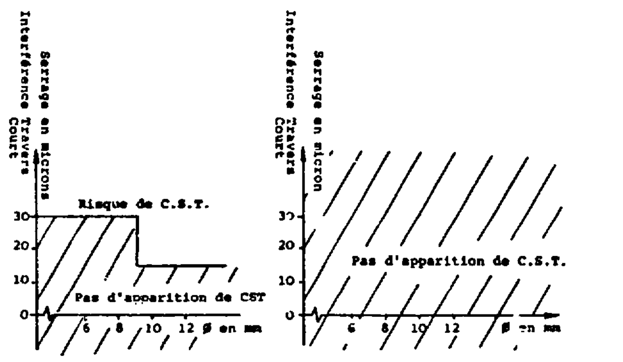
PLANCHE N° 3



EVOLUTION DE LA CONTRAINTE CIRCONFERENTIELLE EN FONCTION DU ø

(Rivets titane dans l'alliage léger avec serrage 10 microns)

PLANCHE N° 4



- Plaquettes externes non peintes (Vapor-Blast avec angles cassés)

- Plaquettes externes peintes (I + P) (Vapor-Blast avec angles cassés) avec ou sans PR au montage.

PLANCHE N° 7

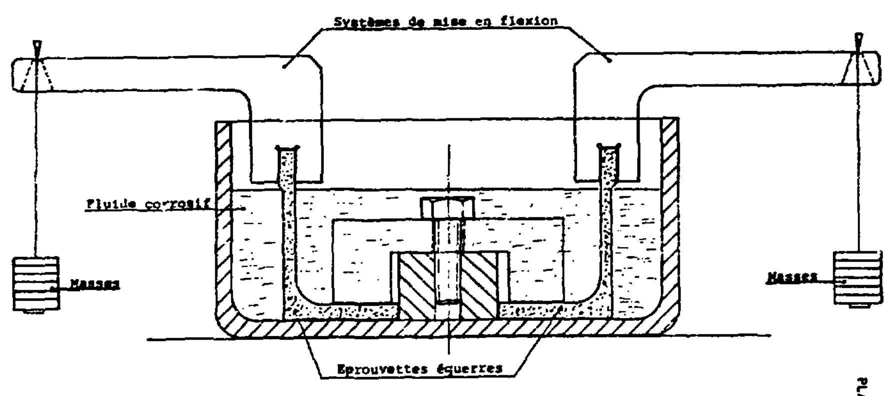
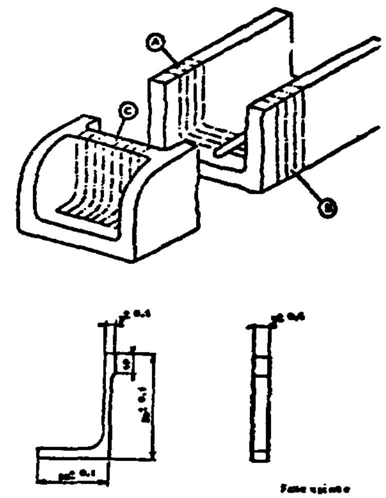


PLANCHE N° 3



Définition et prélèvement des éprouvettes de C.S.T. dans un matricé

PLANCHE N° 8

COURBES DE CONTRAINTE EN FONCTION DE LA DUREE DE VIE

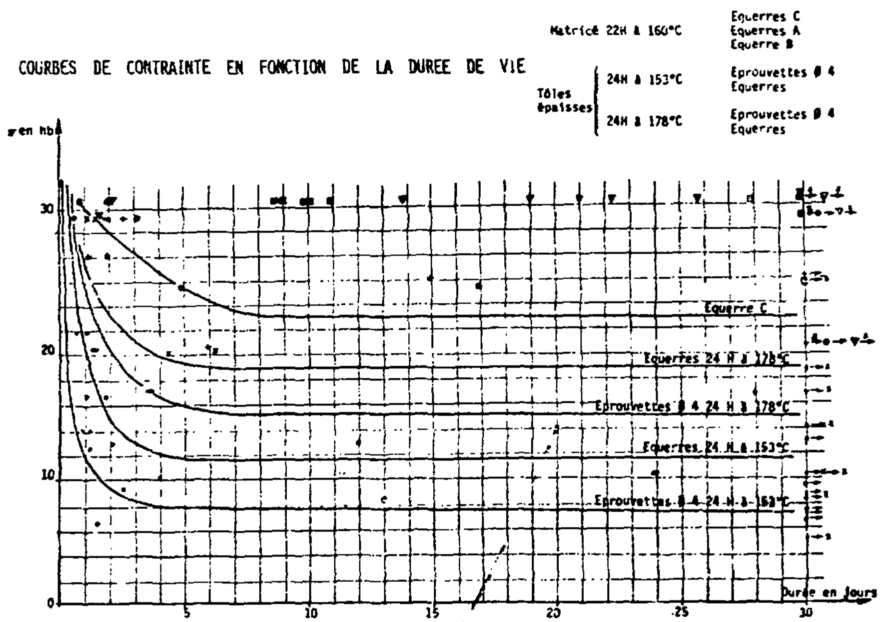
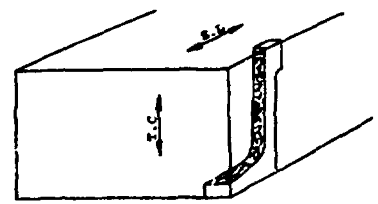


PLANCHE N° 6



Prélèvement des éprouvettes de C.S.T. dans une tôle épaisse en 2214.

PLANCHE N° 9

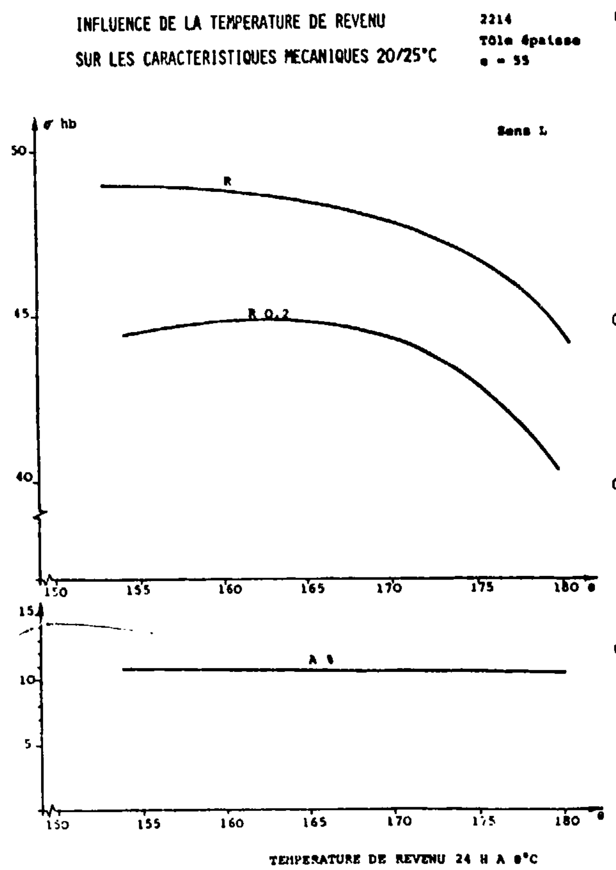


PLANCHE N° 10

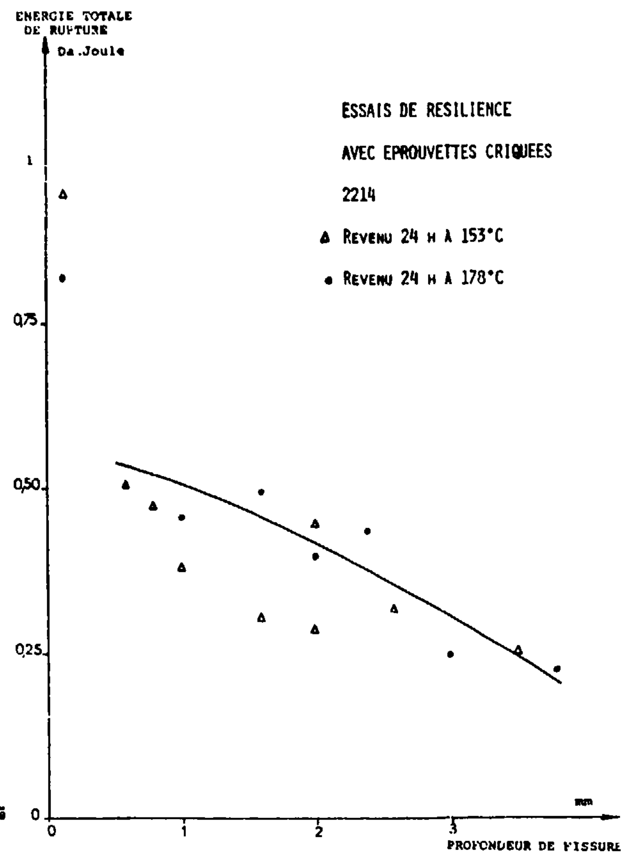


PLANCHE N° 11

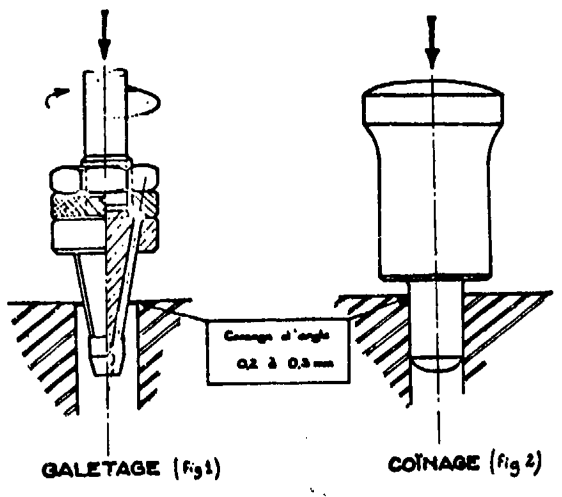
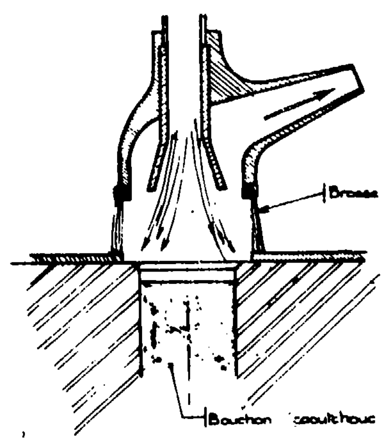
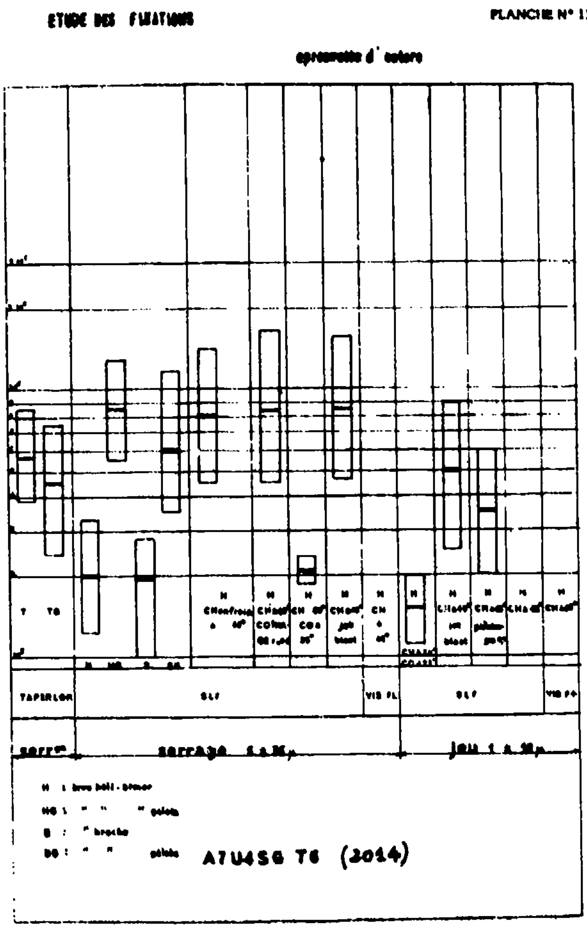


PLANCHE N° 12

JET-BLAST

Abrasif microbille de verre Bright-shot n°12 (240-320 μ)
Pression 4 bars
Temps d'application : de 5 à 10 secondes pour la surface de la buse




ETUDE DES FIXATIONS
PLANCHE N° 13
TAPERLOK
VIS FL
serrage
jeu
broche
A7U4SG T6 (2014)

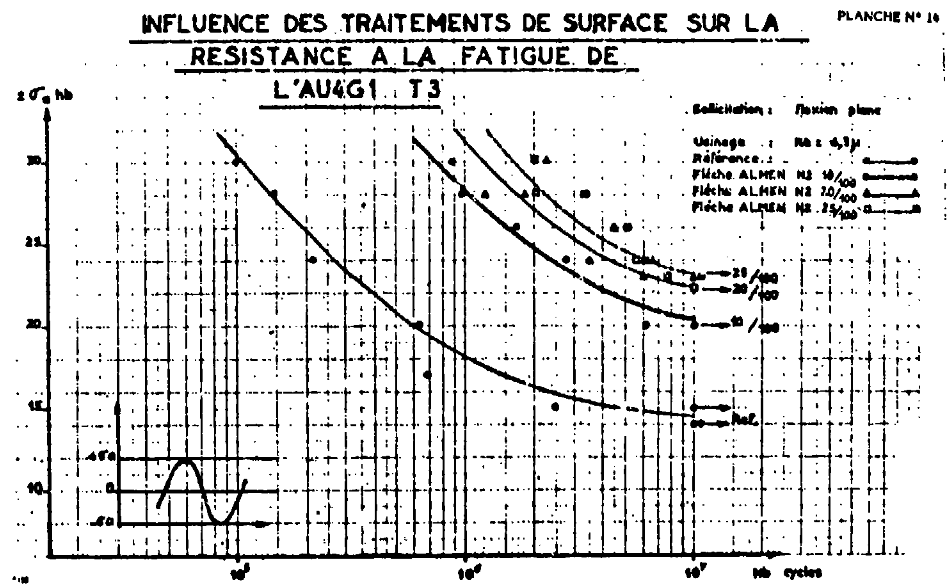

INFLUENCE DES TRAITEMENTS DE SURFACE SUR LA RESISTANCE A LA FATIGUE DE L'AU4G1 . T3
PLANCHE N° 14
Sollicitation : flexion plane
Référence
Flèche ALMEN N2 10/100
Flèche ALMEN N2 20/100
Flèche ALMEN N2 25/100
30
25
20
15
10
10^5
10^6
10^7
Nb cycles
Ref.

PLANCHE N° 15

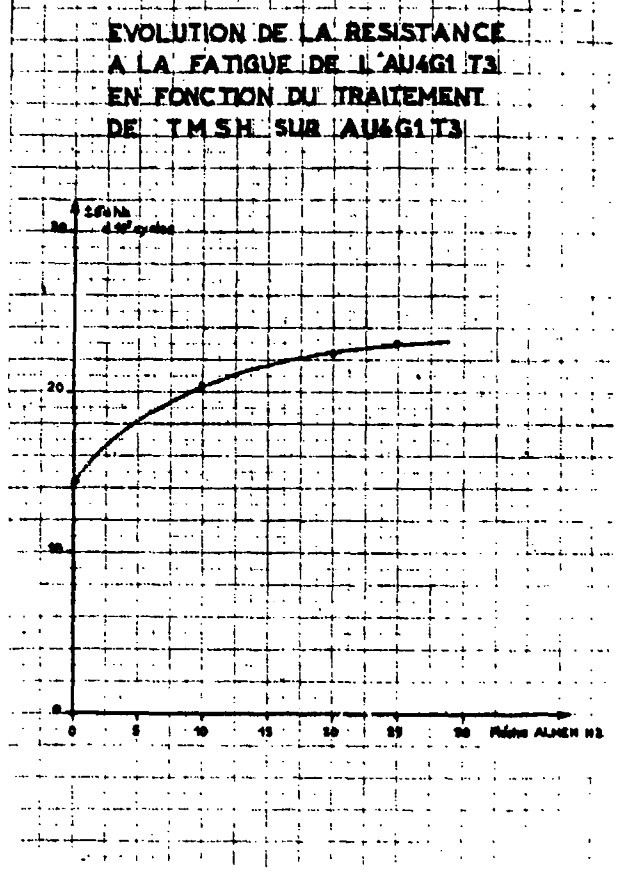


PLANCHE N° 16

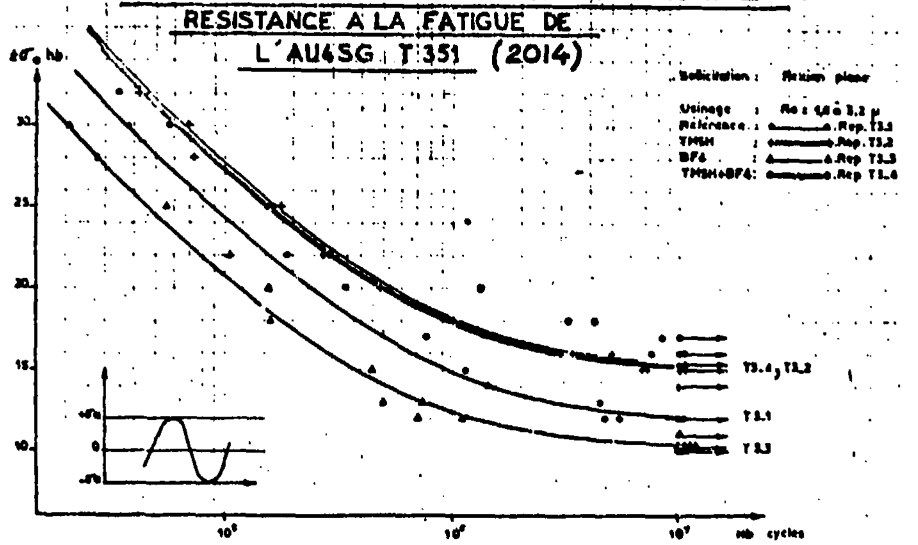


PLANCHE N° 17

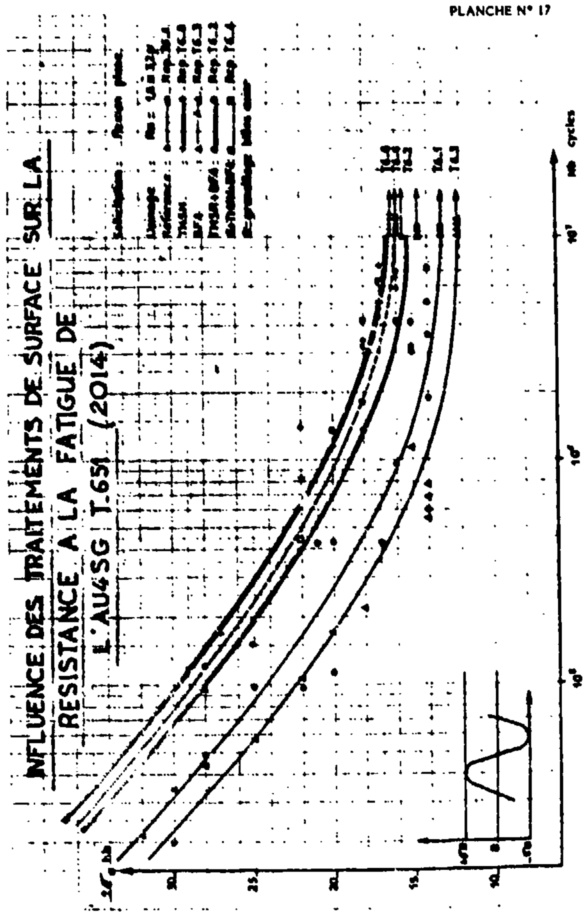


PLANCHE N° 18

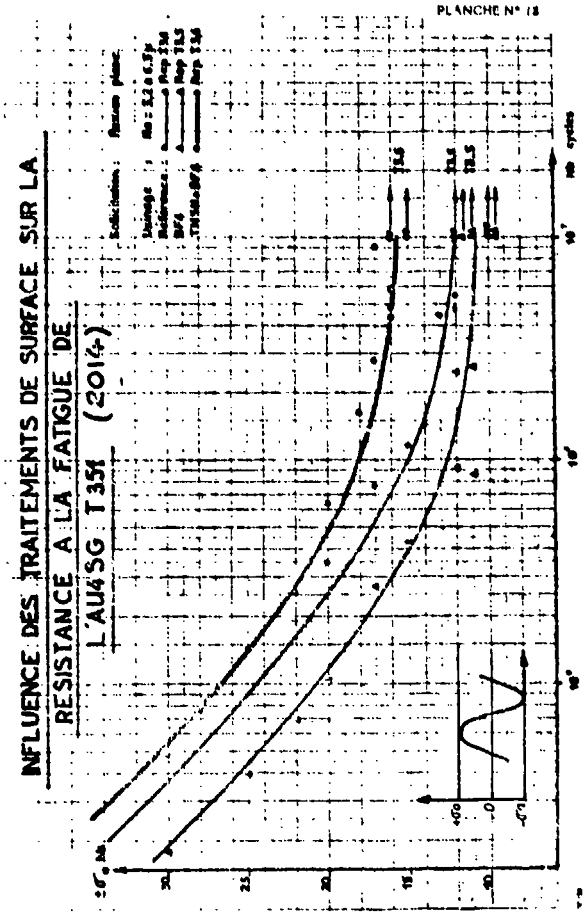


PLANCHE N° 19

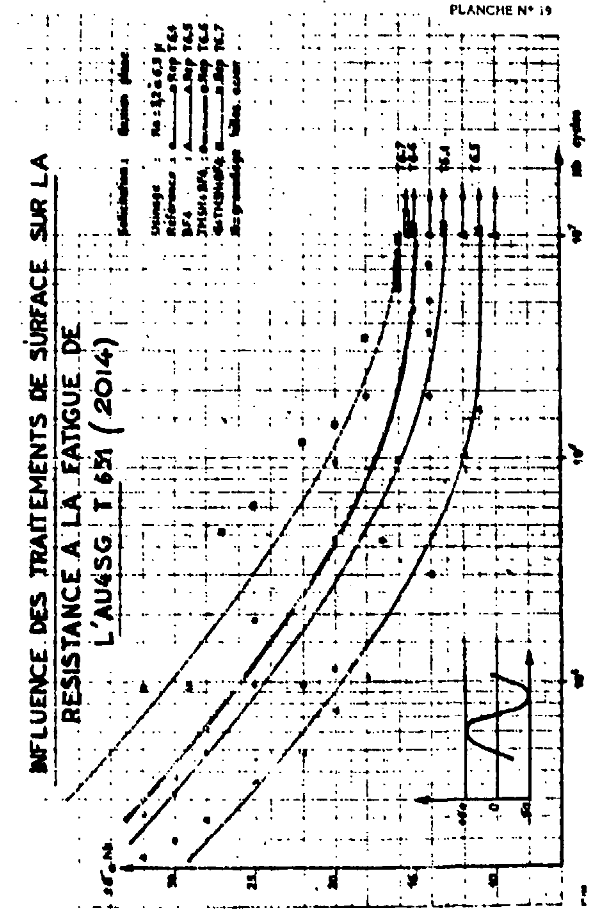
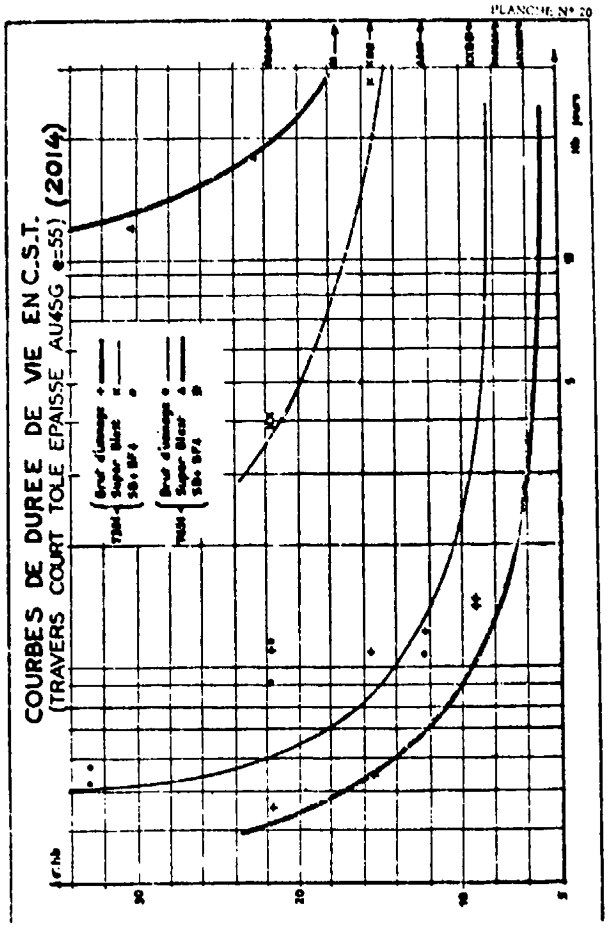


PLANCHE N° 20



RECORDER'S REPORT – SESSION II

by

Sq. Ldr. C.R.Pye, RAF
Central Servicing & Development
Establishment, RAF
Swanton Morley
Dereham, Norfolk NR20 4LJ

There were five papers in Session II. They all had a great deal in common although their content was varied. They all saw the problem with corrosion to be the same. Moreover they all presented roughly the same message for the way ahead. Two of the papers concentrated more on specific case histories whilst one paper concentrated on the general design requirements needed to minimise corrosion and was particularly concerned with military aircraft. One paper related the likely amount of corrosion damage that would occur on military aircraft to the environment at different locations at which the aircraft operated. The final paper was specifically concerned with methods of improving the stress corrosion resistance of T2214 aluminium alloy. The need for and the benefits of a good reporting system was also mentioned in more than one paper as were possible future problems.

All the authors saw the problem of corrosion as serious because of the cost of repairs undertaken by the aircraft operator to rectify corrosion defects. Furthermore because aircraft are generally required to last longer the problem of corrosion is likely to get worse in the future unless positive steps are taken to maximise the resistance of all structures to corrosion.

As in Session I it was evident that the best place and, perhaps the only place, to reduce in-service corrosion costs was at the design stage. The general opinion was that although in-service maintenance was important it would never solve the problem of corrosion and at the best was only first aid. Aircraft maintenance engineers must persuade manufacturers to use the best anti-corrosion design and materials to obtain maximum corrosion free life – even if it costs more.

All the authors again agreed on the sort of design approach required. There were several stages in the design that needed to be considered. These stages were the detailed design, the selection of materials and methods of protection. For detailed design there was a need to control water and humidity, improve inspectability and the need to guard against such things as dissimilar metals. For selection of materials, resistance to the many types of corrosion had to be maximised, the use of unclad/clad materials and heat treatments were also important. For methods of protection, paints, metallic coatings, and other surface treatments like sand blasting were very important. There was always a need to consider the corrosion resistance of materials and perhaps, in the future the designer might give these as much attention as he has given fatigue in the past. There is more of a need to make a compromise between fatigue strength and corrosion resistance although of course these are very much related subjects and fatigue is often started from corrosion.

Some detailed case histories of practical aircraft corrosion problems were presented by two authors. These cases were varied; they included wing skin front spar corrosion, pylon corrosion, fuselage floor and skin corrosion and corrosion of other general attachments. It was interesting that in each case the operator found a way of achieving better protection after the repair. Therefore the question has to be asked, why was this better protection not incorporated by the designer? Obviously with hindsight the question is easy to ask, as the authors realised, but nevertheless it must be asked and maintenance engineers must endeavour to ensure that the designer does better in the future. To improve the future situation, feedback from operating experience to the designer and to official regulations is needed. One author thought that a data bank on solutions would be very useful. The proposed SMP Corrosion Manual on this subject would obviously be a step forward. Another author gave a presentation on the current design requirements for UK military aircraft and showed how they were intended to help the designer but more especially how they would protect the customer. These requirements did not actually ban the use of some materials but they ensured that the fatigue or other benefits of some corrosion prone materials could only be used by negotiation. Another author also suggested that each manufacturer should institute a formal sign off procedure after detailed evaluation for corrosion resistance and protection at the detailed design stage.

The most common causes of corrosion that were discussed were accumulated water or humidity, and other corrosive fluids from toilets and cargo spillages. Abrading dusts and dirt as well as atmospheric pollutants were also cited as corrosion initiators. The most mentioned preventative measure was wet assembly both between mating surfaces and on fastener assembly. Other measures thought essential were adequate drains and airtight sealing of sandwich structures. More than one author stated that the correct and timely application of paint, including proper pre-treatment, was fundamental and the initial corner stone of all corrosion prevention.

The resistance to stress corrosion of the well used aluminium alloy 2214 could be improved without sacrificing its excellent fatigue properties. Heat treatment was crucial. Ageing at 178°C instead of 153°C was shown to have a large benefit as was the use of wet sandblasting in maintaining the fatigue resistance whilst increasing the resistance to stress corrosion. However the question of how the performance would be affected by a subsequent surface scratch was raised.

Programmes in the USA, to try and relate corrosion damage on a military aircraft type to the environment found at the various locations for that type, were presented. Assuming a list of factors that could readily be taken or were available for each site an environmental corrosion rating for each site could be simply calculated. The author showed that such a rating could for 4 out of 5 aircraft types be directly related to the quantity of manhours used for corrosion at each base. Questions raised in this paper were concerned with how the work could be extended to civil aircraft and how the rating could be further improved by taking into account other factors.

Cadmium and chromates were health and environmental hazards and in the future engineers might be forced by legislation to look for replacements for these substances which are widely used during anti-corrosion treatments. Cadmium is the best known protector of steel and there is no alternative as good. Aluminium with small amounts of zinc and other elements added is the most promising substitute found so far, but more research is needed. Chromate salts are extensively used as corrosion inhibitors for light alloys, steels, zinc and Cadmium and it is difficult to imagine an aircraft constructed without some use of chromate salts. Zinc salts of thioglycolic acid have been put forward as an alternative to chromate salts, but again more research is needed. The advent of composite materials offers its own special problems. Two suggestions were put forward for better materials. These were the need for more flexible paints and protective treatments that could be applied in less than ideal conditions.

To summarise, the designer can generally overcome all forms of corrosion by one or more means. However he does have to be aware of the problem in the first place. It is always unsatisfactory to look back and cure problems that arise during service. Moreover, it is generally more difficult or sometimes impossible to cure corrosion during the in-service time as opposed to the design stage. The designer has to spend time designing for corrosion protection. In this day and age where aircraft are required to last longer the designer needs to put as much emphasis into designing against corrosion as he does against designing to prevent fatigue. Building up data on where corrosion occurs and how it was cured is obviously invaluable to the designer – especially for new materials and construction methods. The problems of corrosion costs, how to improve feedback to the designer, and ensure that the designer uses the best anti-corrosion design ... d further addressing.

RECENT DEVELOPMENTS IN MATERIALS AND PROCESSES FOR AIRCRAFT CORROSION CONTROL

SARA J. KETCHAM and JOHN J. DE LUCCIA
Naval Air Development Center
Warminster, Pennsylvania 18974
USA

SUMMARY

This paper describes advances in materials and processes for aircraft corrosion control currently in use and those under development in the laboratory for future use. Areas covered are corrosion preventive compounds, organic and inorganic coatings, alloy selection and heat treatments.

Available materials highlighted are water displacing compounds, sealant primers, aluminum alloys 7050 and 7010 including a state-of-the-art report on the use of exfoliation and stress corrosion resistant tempers.

Materials under development that offer promise of contributing to future advances include water displacing paints, flexible primer, crack arrestment compounds, powder metallurgy, aluminum alloys and substitutes for cadmium plating.

INTRODUCTION

This paper will address material and processes developed by the research and development community that have provided advances in corrosion control of naval aircraft. The subjects to be covered will primarily apply to airframes, although they may also be useful for electronic equipment. First, materials currently available will be discussed, then materials still under development which look promising for the future.

Classical corrosion control involves attacking the problem from three standpoints: interfacial (coatings), internal (metal selection), and external (inhibited environment). All three aspects will be covered here.

CORROSION PREVENTIVE COMPOUNDS

The Naval Air Development Center has pioneered in the development of water displacing compounds.(1) These compounds are:

AML-350 - an ultra thin water displacing corrosion preventive compound which dries to a soft film;

AMLGUARD - a water displacing, corrosion preventive which dries to a hard, clear finish.

The need for such materials is occasioned by the difficulty of performing corrosion control procedures in a marine environment. Areas where paint has cracked or chipped leaves bare metal exposed. The mechanism by which these compounds displace water from the surface is shown in Figure 1.(2) The essential elements involved are: (1) the compound spreads over the substrate completely wetting it, (2) it is immiscible with water, therefore does not retain water, and (3) it is preferentially adsorbed, penetrating under the water droplets.

AML-350 is applied to a film thickness of 2 to 5 µm. It is composed of a petroleum sulfonate and a mineral spirits type solvent. The combination of these materials allows the coating to spread over metal and creep under water droplets on a metal surface, thus displacing the water. Eventually the solvent evaporates and the petroleum sulfonate remains, forming a soft, thin, oil-like film. This film isolates the metal from the environment, thus acting as a temporary passive corrosion preventive. The petroleum sulfonate also assists in protection against corrosion by performing as a corrosion inhibitor.

AML-350 is intended for use on internal metallic parts and electrical connectors. It has widespread use on airborne electronic equipment. It is generally not intended for use on external airframe areas because of its soft condition, but under adverse weather conditions or when aircraft are liberally water soaked, it may be applied as a temporary protective measure.

AML-350 is covered by military specification MIL-C-0081309C.(3)

AMLGUARD contains polymeric resins which upon application and cure form a dry, hard film with a thickness of 25.4 to 50.8 µm (1 to 2 mils). It is a combination of organic solvents, silicone and silicone alkyd resins, barium petroleum sulfonate, and several other additives. It also displaces water by spreading over the metal and creeping under the water droplets. Drying occurs via solvent evaporation, leaving a solid film. Although AMLGUARD dries to the touch in 18 hours, it continues to cure for 1 to 3 months, forming a hard, flexible finish. Corrosion protection is provided by the physical barrier of the coating and also by barium petroleum sulfonate and alkyl ammonium organic phosphate performing as corrosion inhibitors. Figure 2 illustrates the protection afforded by AMLGUARD.

This material is intended for temporary use on external aircraft parts where it offers excellent corrosion protection. It has also been recommended for use on leading edges of aircraft wings and helicopter blades and on exhaust and gun blast areas, as well as many other aircraft components such as wheels, wheel wells, cables, landing gear, etc. where erosion resistance and corrosion protection is necessary. AMLGUARD has been successfully used on mild steel, stainless steel, aluminum, magnesium, zinc, cadmium, copper and brass. It should not be used on lubricated surfaces, electrical contact areas, form in place gaskets, removable fasteners or moving parts.

AMLGUARD is covered by military specification MIL-C-85054.(4)

SEALANTS

Elastomeric sealants are widely used on naval aircraft to seal out the environment. The most popular at the present time are the polysulfide sealants which contain soluble corrosion inhibitors. These are covered by military specification MIL-S-81733.(5) Ordinary sealants can minimize corrosion of metals in high humidity environments, but cannot prevent it completely because all polymers are permeable to moisture. The inhibitive sealant is very effective when used in faying surfaces and butt joints, for wet installation of fasteners and over fastener patterns and to insulate dissimilar metals Figure 3. (6)

It is anticipated that the use of elastomeric sealants (polyurethanes and silicones as well as polysulfides) will increase in the future due to their ability to accomodate the dynamic loads imposed on aerospace equipment without cracking.

SURFACE TREATMENTS FOR ALUMINUM ALLOYS

With regard to surface treatments for aluminum alloys, there has been a return to anodizing for new weapons systems rather than chromate conversion coatings. Both sulfuric and chromic acid anodizing are being used. Anodized surfaces provide more corrosion protection, abrasion resistance and long-term durability than chromated surfaces. Sealing of anodized coatings has always been recommended and recent work at NADC has re-emphasized the importance of the type of water used to seal non-clad aluminum surfaces. Sealing in tap water resulted in inferior corrosion resistance and paint adhesion as compared to that of sealing in distilled water.

The paint system used on naval aircraft, the MIL-P-23377 epoxy primer and the MIL-C-82386 polyurethane topcoat, has performed better than any previous system. It is durable, abrasion resistant, retains its gloss well, does not chalk or craze, and is easy to clean. Its main drawbacks are its lack of low temperature flexibility which causes it to crack around fasteners and the fact that both primer and topcoat are two-part systems. Laboratory work to improve the paint system will be described in a later section.

ALLOY SELECTION AND HEAT TREATMENT

The advent of the heat treatable 7000 series aluminum alloys provided a boon to aircraft designers. The high modulus, high strength, and low weight of these alloys made them ideal for the high performance of advanced aircraft. Their susceptibilities to intergranular corrosion, exfoliation, and stress corrosion cracking made them less than desirable in marine environments. It was discovered that if these alloys were systematically overaged, their susceptibilities to these forms of attack would be materially lessened if not totally eliminated. Thus the T73 temper was born. As is usually the case with most "fixes," a price had to be paid. There is an approximate 10% strength loss accompanying the T73 overaging treatment. The T73 temper replaced the standard T6 temper on many military aircraft where designs could be altered or the strength loss tolerated.

More recently newer 7000 series alloys have been developed with specific resistance to intergranular attack and environmental embrittlement. Most of these new alloys such as 7050 and 7010 owe their lessened susceptibility to the presence of zirconium. Professor DiRusso in Italy first identified the beneficial effects of this element in Al-Zn-Mg alloys.(7) These newer alloys also pay particular attention to the "cleanliness" of the microstructure. It contains lower concentrations of the tramp elements, iron and silicon, and therefore has a greater fracture toughness. Aluminum alloy 7050 was developed under the guidance of the Naval Air Systems Command by Alcoa.(8) In the T73X temper, it provides the best stress corrosion resistance with the highest strength of any commercial aerospace aluminum alloy.

Alloy 7010, developed by Alcan Plate Ltd., has, in the T73X temper, recently become competitive with 7050.

Some recent work at an Israeli aerospace company indicates that a pre-aging treatment of 7075 alloy renders immunity to stress corrosion cracking (K_{ISCC} is raised by a factor of three) without any sacrifice in strength. This treatment, which is called retrogression and re-aging, bears watching.(9)

The preceding paragraphs have described materials currently in use, or available, to minimize environmental deterioration of airframes. Materials and processes under development in the laboratory will now be addressed.

MATERIALS UNDER DEVELOPMENT

Water Displacing Paint

This material is a pigmented coating which will displace water, dry and subsequently afford corrosion protection. It is composed of a petroleum sulfonate, silicone-alkyd resin, organic solvents, pigments and other organic additives. The mechanism by which this material displaces water is the same as that discussed earlier. This pigmented coating dries to a hard, flexible finish which protects the substrate from corrosion by:

1. The physical barrier of the coating.
2. Corrosion inhibiting pigments; i.e., molybdates and chromates.

This water displacing paint is designed as a touch-up paint for exterior surfaces of aircraft where original paint has cracked or chipped and total repainting is not feasible. Such a situation is confronted on operational aircraft deployed on board aircraft carriers where paint touch-up is necessary but must be completed quickly and efficiently. This paint was designed to be applied during deployment and to last indefinitely until total repainting of the aircraft is necessary.

Reports from an initial evaluation of the paint by the Fleet indicated it performed well. Some settling problems remain to be resolved.

Flexible Primer

The current Navy paint scheme for high-performance aircraft includes the application of MIL-P-23377 epoxy primer, MIL-S-8802 or MIL-S-81733 polysulfide sealant, and MIL-C-83286 polyurethane topcoat. This system has several limitations. The primer possesses poor low-temperature flexibility, while the sealant is difficult to apply due to its high viscosity and short pot life. The ideal solution would be a single application of an elastomeric sealant-primer with the adhesion of a primer and the flexibility of a sealant. This would also eliminate the need to handle two separate materials, resulting in a significant cost savings to the government.

A comparative evaluation of a number of inhibited elastomeric coatings including a polysulfide, a polyurethane and an epoxy-polyurethane system is being made. Such properties as the hardness, adhesion, strength, flexibility, erosion resistance, corrosion resistance and ease of application of these materials will be determined and an optimum material selected.

Development of an Aluminum Plating Process

There is increasing pressure to eliminate the use of cadmium by DoD activities because of its toxicity. While no single coating has been found to replace cadmium in all aircraft applications, aluminum has been found to be a very good alternate coating material in many applications requiring good corrosion resistance and minimal effect on fatigue properties. Only two aluminum coating processes are currently commercially feasible, vacuum deposition and ion vapor deposition. Vacuum deposition has relatively poor covering power and adhesion is often only fair. Ion vapor deposition is proprietary and facilities for its application are complex and cannot meet the demand for the coating. Other methods exist, but they have not been developed sufficiently to be of real commercial value.

NADC is involved in an effort to develop a method to electroplate an aluminum coating from a molten salt bath. To date the process has been scaled up from a small bath to a forty liter bath. A schematic of the bath is shown in Figure 4. It has been demonstrated that a coating of aluminum-manganese can be deposited on aluminum, titanium and steel substrates with conventional pretreatments and with excellent adhesion. The coating can be chromate conversion coated but not anodized.

The molten salt plating process has an advantage over the ion vapor deposition in that the throwing power is better and recesses and holes can be coated. Work is in progress to optimize the plating parameters. Following completion of that phase, a pilot plant production set-up will be attempted.

Phase Transfer Inhibitors (PTI)

A method was developed in-house by which ions could be solubilized in organic media using phase transfer catalysis (PTC). This method has been used to develop an entirely new vehicle for corrosion inhibitors. These have resulted in inorganic inhibitors incorporated in organic phases, i.e., an oxidizing anion dissolved into an organic non-polar solvent, in this case, mineral spirits. The technique by which this is accomplished has been published elsewhere and will not be repeated here.(10) The inorganic inhibitors being used include sodium dichromate ($Na_2Cr_2O_7.2H_2O$), sodium borate ($Na_2B_4O_7.10H_2O$), sodium nitrite ($NaNO_2$), sodium molybdate ($Na_2MoO_4.2H_2O$), potassium hexachloropalladate and ammonium hexanitrato cerate [$(NH_4)_2Ce(NO_3)_6$].

Evaluation of these new phase transferred inorganic inhibitors (PTI) was first carried out for the general corrosion inhibition of steel and aluminum alloy in highly aggressive environments. A salt fog chamber was used and both AISI 1020 steel and 7075 aluminum alloy panels treated with PTI dichromate were tested. A four-day test exposure of such panels showed no observable corrosion of either steel or aluminum alloy specimens. In another test PTI dichromate inhibitor was added into alkyd enamel coating and then tested on 7075 discs in a 5% NaCl salt spray chamber for about four months. The specimen coated with PTI dichromate showed much less attack than the control with only alkyd enamel coating protecting it. A marked improvement in corrosion protection was also found when PTI dichromate was added to epoxy paint primer and temporary preservatives and a corrosion preventive compound (AMLGUARD).

Crack Arrestment Compounds

The effect of the inhibitors was most interesting in the study of corrosion fatigue, particularly when they were used in combinations. Thus, a number of low cycle corrosion fatigue tests were carried out using notched bend bar specimens (10" x 2" x 1/2" size, fracture mechanics type) fabricated from high strength (1250-1350 MPa) vacuum arc melted 4340 steel. The specimens were fatigue pre-cracked before testing and then mounted on an Instron machine enclosed in a controlled humidity chamber. The specimens were cycled between loads of 1500 to 150 lbs at a frequency of about 0.16 Hz. The load value and the pre-crack length were chosen to yield a minimum fracture mechanics stress intensity factor of approximately 23 $MPa\sqrt{mm}$ in dry (i.e., less than 15%) R.H. The test inhibitor or inhibitors were applied by injecting the solution into the pre-cracked notch area of the specimen before and after loading. The specimen was loaded in tension-tension. The crack growth of the specimen was monitored as a function of time and cycles. The details of the mechanical testing and fracture mechanics calculations are described elsewhere. The corrosion fatigue tests were carried out in both the high humidity (moist air) and in chloride containing moist air environments. The PTI inhibitors were then evaluated for their crack arresting properties. The results of these tests are reported in Table I which shows the suggested mechanism by which the inhibitors are functional, the total fatigue life before overload fracture, the crack growth rate in the region where it is independent of stress intensity factor and the stress intensity factor where it is independent of crack growth rate.

The data in Table I show that PTI dichromate, nitrite and borate are very effective in retarding crack growth rate of 4340 steel by more than an order of magnitude when compared to moist air test with no inhibitor present. In terms of fatigue life the inhibition was almost five times more effective. Almost every PTI compound tested, i.e., even cerate and hexachloropalladate, showed significant crack growth inhibition. However, in the presence of chloride (NaCl) the results were entirely different. The dichromate + nitrite + borate system did not shown much improvement. But when PTI molybdate was added, the crack growth inhibition properties of the compounds were restored and the fatigue life of specimen was extended by a factor of 4. Figure 5 presents these results graphically.

The use of phase transfer inhibitors in pre-cracked stress corrosion cracking in aluminum alloys is presently being studied. Preliminary tests using dichromate, nitrite, borate, molybdate as well as dichromate, phosphate, silicate inhibitor combinations show the cracking rate to be perceptibly decreased in aluminum alloy 7075-T6 exposed to salt laden moisture (Figure 6).

The field of phase transfer catalysis and organometallic chemistry appears to provide a new class of corrosion inhibitors which will probably have wide applications in materials such as coatings, corrosion preventive compounds and crack arrestment compounds.

Powder Metallurgy Aluminum Alloys

With regard to alloys and heat treatment, considerable work is in progress on aluminum alloys (and others) made by high density powder metallurgy (P/M) processing rather than conventional ingot metallurgy (I/M) practices of casting and working. P/M processed materials have finer and more homogeneous microstructures. An important advantage of P/M high strength aluminum alloys compared to I/M is that they can be aged to considerably higher yield strength values without losing their resistance to stress corrosion cracking.

Considerable interest is being shown in the Alcoa P/M alloy CT91, a 7XXX composition type for aircraft use. An aircraft company has investigated extrusions made from this material and compared their properties with those of 7075-T6 extrusions. At comparable strength levels, the CT91 extrusions had higher corrosion resistance and improved fatigue properties. A weight payoff study for a V/STOL aircraft showed a 10% weight saving by replacing existing aluminum alloys.

Considerable development work is still going on with P/M alloys, but it is anticipated that their use in aircraft is not long in coming. Surface treatment of these alloys will probably require some investigation since there is evidence they do not anodize like conventional wrought alloys.

This has been a brief discussion of the materials and processes currently being used for corrosion control on naval aircraft. Some of the more important in-house efforts and ongoing research in the Aero Materials Division at the Naval Air Development

Center are highlighted. Fighting corrosion is a never ending battle, but even small successes can provide a payoff in reduced maintenance manhours and improved reliability.

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TABLE 1

EFFECT OF FUNCTIONAL PROPERTIES OF VARIOUS CRACK ARRESTMENT INHIBITORS ON LOW-CYCLE FATIGUE OF HIGH STRENGTH 4340 STEEL

	INHIBITORS APPLIED TO NOTCH AREA	MECHANISMS INVOLVED	CRACK GROWTH RATE MICRO-IN./CYCLE	STRESS INTENSITY FACTOR ΔK, KSI $\sqrt{IN.}$	FATIGUE LIFE, CYCLES
	DRY AIR ONLY	NO CORROSION	12	70	17,000
MOIST AIR ONLY	NO INHIBITOR USED	SEVERE CORROSION AND H.E.	110	33	1,800
MOIST AIR ONLY	DICHROMATE	PASSIVE FILM FORMATION	42	52	6,800
MOIST AIR ONLY	NITRITE + BORATE	MOSTLY pH ADJUSTMENT	65	35	3,300
MOIST AIR ONLY	HEXAPALLADATE	ACCELERATE H RECOMBINATION	45	>40	4,000
MOIST AIR ONLY	LANTHANUM NITRATE	H GETTERING ACTION	50	>40	4,600
MOIST AIR ONLY	DICHROMATE + NITRITE + BORATE	PASSIVATION AND pH ADJUSTMENT	27	55	9,000
MOIST AIR ONLY	CERATE + NITRITE + BORATE	PASSIVATION AND pH ADJUSTMENT	38	45	6,400
MOIST AIR + CHLORIDE	NO INHIBITOR USED	SEVERE CORROSION AND SEVERE H.E.	150	32	1,200
MOIST AIR + CHLORIDE	DICHROMATE + NITRITE + BORATE	NO PASSIVATION, SEVERE H.E.	200	34	1,200
MOIST AIR + CHLORIDE	MOLYBDATE	SOME PASSIVATION AGAINST CHLORIDE	61	46	4,500
MOIST AIR + CHLORIDE	DICHROMATE + NITRITE + BORATE + MOLYBDATE	PASSIVATION, pH ADJUSTMENT AND CHLORIDE RESISTANCE	28	48	6,500

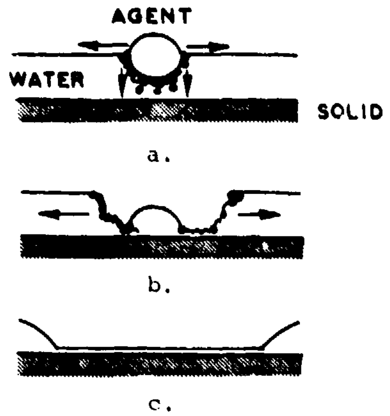

Figure 1. Mechanism of Water Displacement (2)

a. Displacing agent applied to water surface, mixture with water begins.
b. Agent reaches the surface while pushing water aside.
c. Preferential adsorption of the agent over water allows water to be displaced from the surface.

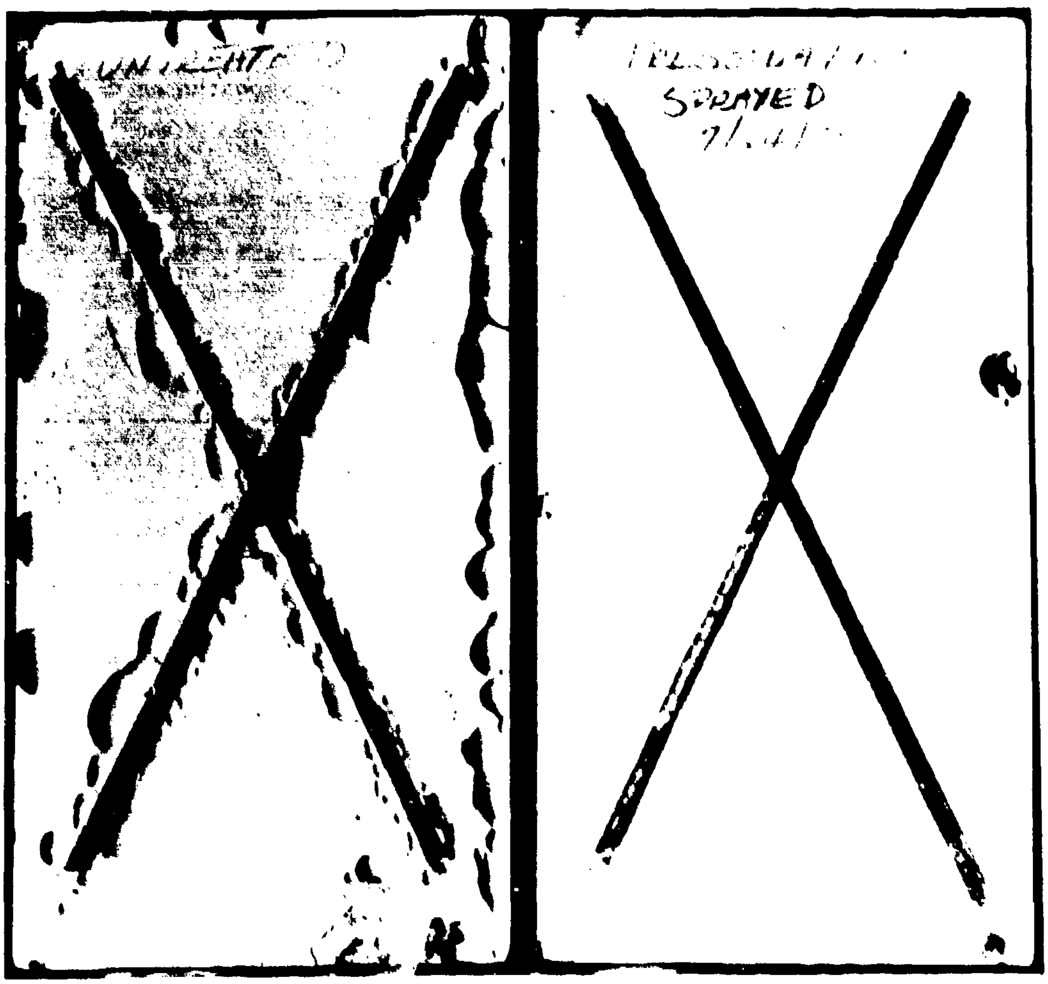

Figure 2. Protection afforded by AMLGUARD to a scribed, painted aluminum alloy panel during a 90 day exposure to 5% NaCl/SO_2 Salt Spray Test.

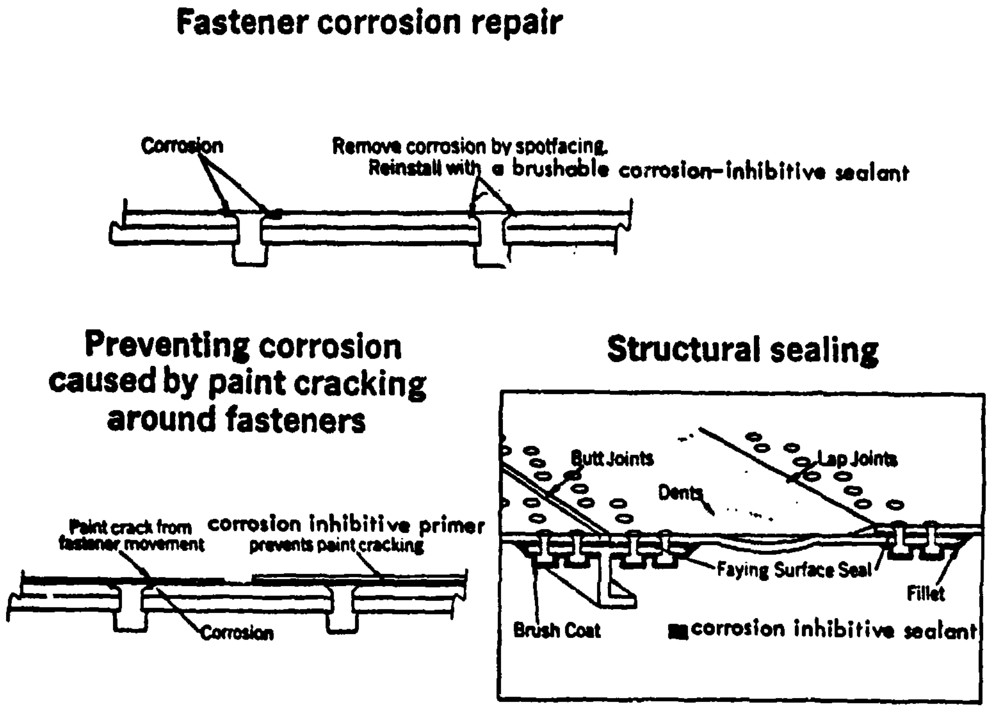

Figure 3. Typical Aircraft Applications of Inhibitive Sealants (6)

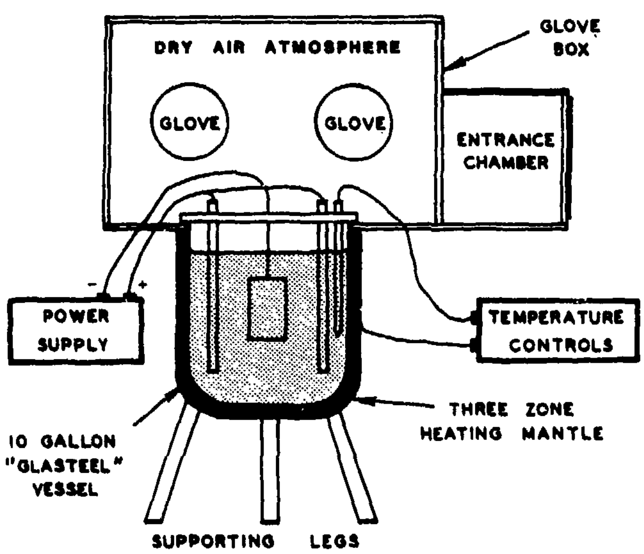

Figure 4. Schematic of Al-Mn Molten Salt Plating Bath

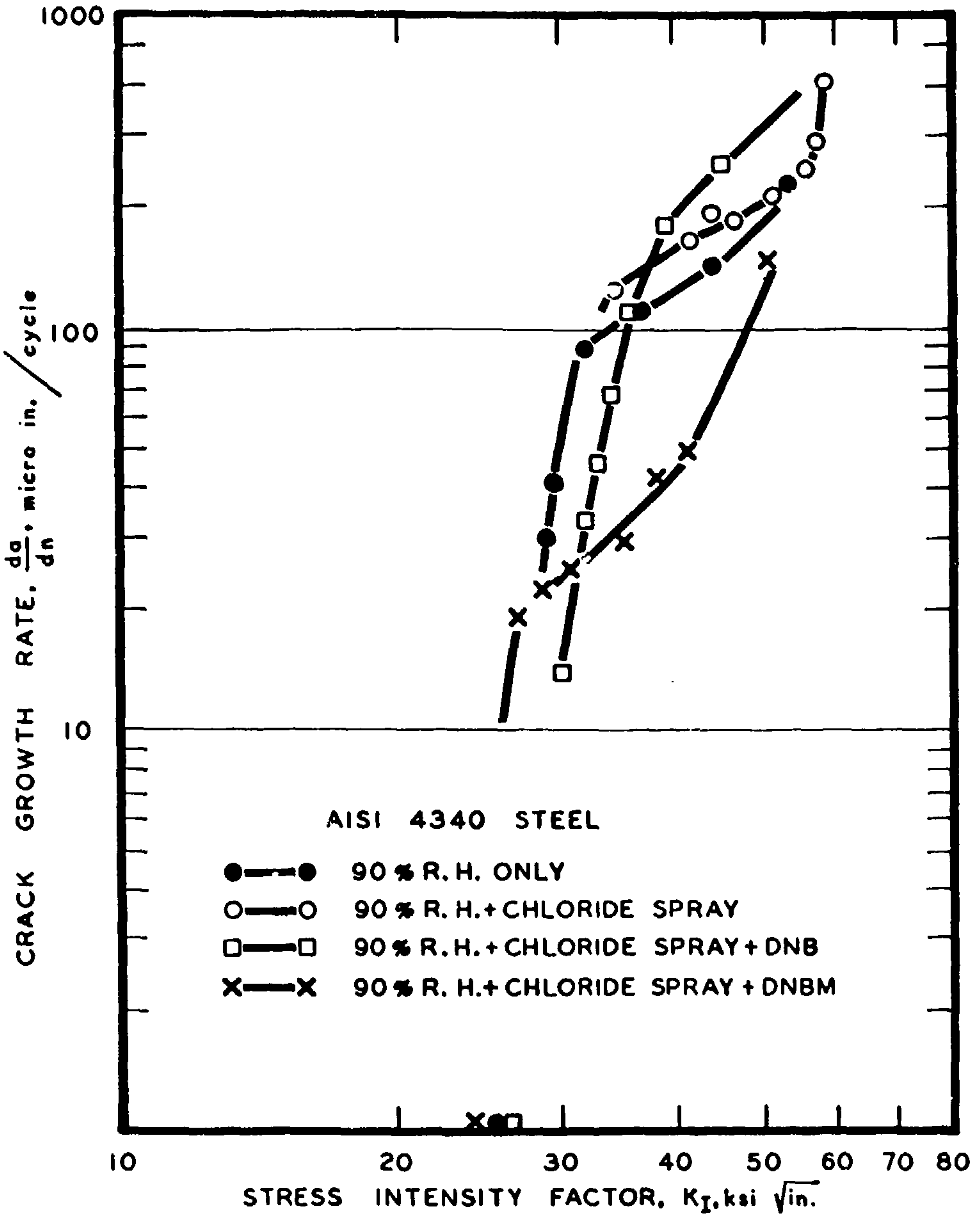

Figure 5. Crack Growth vs. Stress Intensity Factor for Notched Bend Bar Corrosion Fatigue Tests of 4340 Steel in Various Environments.

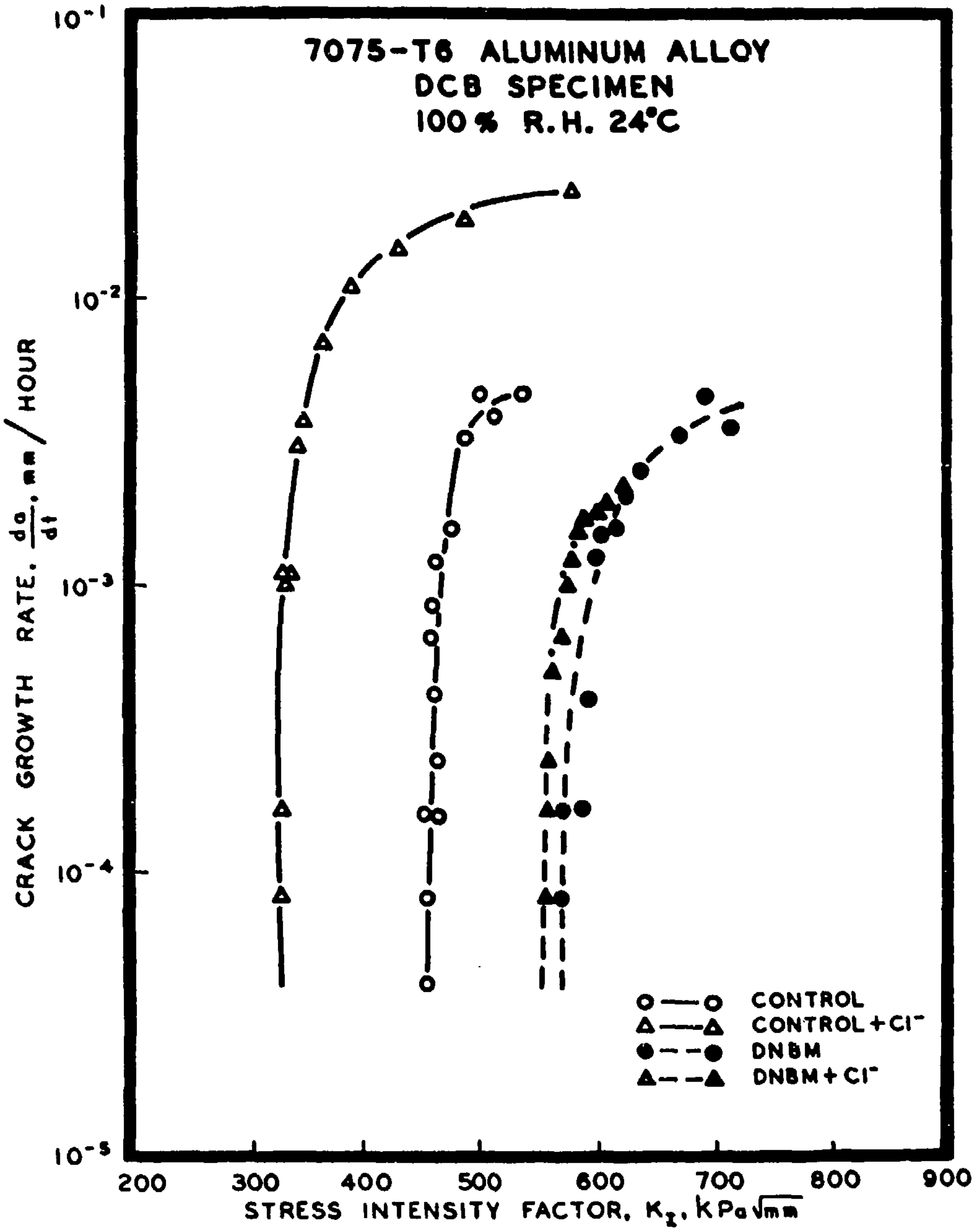

Figure 6. Crack Growth Rate vs. Stress Intensity Factor for DCB Stress Corrosion Specimens of 7075-T6

NEW CONCEPTS IN MULTIFUNCTIONAL CORROSION INHIBITION FOR AIRCRAFT AND OTHER SYSTEMS

M. Khobaib
Systems Research Laboratories, Inc.
2800 Indian Ripple Road
Dayton, OH 45440

F. W. Vahldiek
and
C. T. Lynch
Air Force Wright Aeronautical Laboratories
Materials Laboratory (AFWAL/MLLN)
Wright-Patterson Air Force Base, OH 45433

SUMMARY

The development of inhibitors for aerospace applications such as automated rinsing of aircraft requires systems of high solubility, low toxicity, and reasonable cost which are effective on a wide variety of high-strength susceptible alloys. Chromate-based products, in combination with polyphosphates, have been reasonably effective against corrosion of ferrous and nonferrous metals and alloys and are presently the most widely used inhibitors. The use of chromates, however, has been the subject of ecological concern, and the present investigation involves the performance of nonchromate inhibitors, with emphasis on a borax-nitrite-based formulation. Multifunctional nonchromate inhibitors have been developed which are effective in preventing localized corrosion and accelerated crack growth, as well as general corrosion. Field evaluations of these inhibitors are underway.

INTRODUCTION

Over the past four years, a considerable number of studies have been conducted in the United States regarding the total cost of corrosion prevention and control for aircraft. The inescapable conclusion is that total corrosion costs in terms of life-cycle management and maintenance of aircraft represent an intolerable burden to the U.S. Air Force in maintaining force effectiveness at a reasonable cost to the taxpayer. A recent study conducted by NBS [1] has indicated that the total corrosion cost for one year was over 70 billion dollars nationally, with costs to the USAF estimated to exceed one billion dollars. In order to minimize these costs, the USAF has been searching for ways to combat corrosion in all its forms. Several years ago a study [2] conducted by the U.S. Navy on corrosion prevention in carrier-based aircraft revealed that by merely rinsing the aircraft with water to remove detrimental particles such as salt and ash, a considerable savings could be realized in terms of corrosion maintenance. By late 1975, the USAF had made a decision to build a rinse facility for the F-4 aircraft and to install it under AFLC/WRALC and TAC at MacDill Air Force Base. At the corrosion managers conference at WRALC in the fall of 1975, questions concerning hard-water rinsing as opposed to inhibited or demineralized-water rinsing were discussed [3]. In the rinsing of aircraft, the possibility exists that water will be trapped in crevices or so-called dry-bay areas and that trapped hard water will cause serious corrosion problems and hence completely jeopardize any advantage of hard-water rinsing as a corrosion-control method. Therefore, the incorporation of a low concentration of a non-toxic water-soluble inhibitor into the rinse facility was suggested.

The use of inhibitors to reduce costs also received impetus as a result of the conclusions reached at the 1975 AFML-AFOSR Corrosion Workshop [4]. The expanded use of inhibitors to reduce the costs and problems associated with corrosion in aerospace systems was recommended as a cost-effective, flexible, and widely applicable approach.

Although chromate-based [5,6] corrosion inhibitors have been widely used to combat corrosion of ferrous and nonferrous metals and alloys, the use of chromates has recently been the subject of ecological concern. The present investigation was carried out to search for alternatives to chromates, one such alternative being a borax-nitrite-based inhibitor. The value of borax nitrite as a corrosion inhibitor has long been recognized [7,8]. Earlier work [9] has shown a borax-nitrite combination to be very effective in controlling general corrosion as well as crevice corrosion of high-strength steels. However, this combination was not found to be effective against the corrosion of other ferrous and nonferrous metals and alloys. The present study was conducted to develop a nontoxic multifunctional corrosion inhibitor (which would be effective against corrosion of ferrous and nonferrous metals and alloys--mainly aluminum and copper alloys) to be incorporated into the USAF Automated Rinse Facility at MacDill Air Force Base in Tampa, FL. More than one hundred inhibitor compounds and formulations were surveyed with regard to their effect upon electrochemical behavior, general corrosion, galvanic corrosion, crevice corrosion, and corrosion fatigue. As a result a borax-nitrite-based inhibitor was developed and is currently being evaluated in the Automated Rinse Facility at MacDill Air Force Base. This mixture contains no chromate, is biodegradable, and offers other important advantages over chromate-based combinations which will be discussed.

GENERAL CONSIDERATIONS FOR INHIBITORS

Several commercial inhibitors are available for various service applications such as cooling-tower circuits, central-heating systems, and automotive radiators. These formulations are normally combinations of several classes of inhibitor compounds, some functioning as anodic inhibitors and others as cathodic inhibitors. Commercial experience has shown that such combinations are often more effective due to some synergistic [10] effect. Unfortunately, most of them are optimized for a specific application. The results of work conducted at the Air Force Materials Laboratory have demonstrated an encouraging inhibition effect of borax-nitrite upon high-strength steels [11]; chromates have not been found to be so effective in the presence of chloride ions [12]. The promising results of the borax-nitrite combination were observed in crack-growth experiments--both in static tests and cyclic corrosion-fatigue tests--but this combination was not effective in inhibiting the corrosion of high-strength aluminum alloys, copper, and other alloys used in aircraft structures and in the Rinse Facility. However, the encouraging results obtained on high-strength steels served as the impetus for further exploration.

In order to systematize the development of new inhibitor formulations and current commercial products, it is desirable to establish some guidelines for selection of inhibitors for further experimental screening. In Table 1 some of the more important considerations and possible compound types are listed. Most of these are obvious considerations, with a few being particularly important for aerospace or other applications where high-strength alloys are utilized. These considerations require effectiveness to retard or eliminate hydrogen embrittlement, stress-corrosion cracking, and corrosion fatigue which can lead to catastrophic cracking failure in high-strength alloys [11].

The first and foremost task in the screening of the inhibitors was the question of toxicity. All the inhibitor formulations which were obviously toxic (based upon information in the literature [13]) were eliminated first--chromates, aniline, and arsenic additions being obvious examples.

The use of the other guidelines delineated in Table 1 is discussed in more detail in a previous report on the development of the rinse inhibitors [14]. These guidelines led to a selected list of inhibitor compounds and formulations for subsequent experimental screening. Special solutions were employed, as discussed in the experimental section, to reproduce the rinse water used at the Automated Rinse Facility and to reproduce more aggressive media based upon possible high-chloride contamination of the rinse water upon recycling after use on the aircraft.

EXPERIMENTAL

Since the inhibitor was being developed for aircraft rinsing, the materials chosen to be tested were those commonly used in aircraft structures and in the Rinse Facility. Three high-strength aluminum alloys--2024-T3, 7075-T6, and 7050--along with high-strength steel, 4130, 4340, cast iron, and 70-30 brass were obtained from a local supplier (Jorgenson Steel, Dayton, OH).

Standard 60 x 30 x 3.125 mm test coupons were used for immersion tests on aluminum alloys. Smaller rectangular sheets with dimensions 75 x 25 x 3.125 mm were used for high-strength steel, brass, and cast iron. These were mechanically polished with emery paper up to 400, cleaned thoroughly in acetone and alcohol, and in several instances finally degreased with petroleum ether. A hole, nearly 5 mm in diam, was made close to one end; and the specimens were suspended by means of a fish line (nylon thread). The maximum duration of these tests has been up to 30 months, but most of the test specimens were immersed in the respective electrolytes for 90 days.

The working electrodes for the electrochemical tests were 25-mm-square pieces which were carefully mounted in resin and were tapped with 3-48 thread for attaching to the electrode holder. All electrochemical tests were carried out in accordance with ASTM Standard G5-72, "Standard Recommended Practice for Standard Reference Method for Making Potentiostatic and Potentiodynamic Standardization Measurements." The measurements were conducted using an automated PAR unit consisting of a corrosion cell, potentiostat/galvanostat, log converter, programmer, and X-Y recorder.

A series of systematic tests were conducted which involved the screening of 1) anodic inhibitors (single component, multicomponent), 2) cathodic inhibitors (single component, multicomponent), 3) a combination of anodic and cathodic inhibitors, and 4) multifunctional systems containing the anodic-cathodic inhibitors. The screening of a large number of combinations was conducted by the potentiodynamic polarization technique and weight-loss methods.

In the immersion tests, the weight loss per unit of surface area of the specimens in different electrolytes was converted to mpy (mils per year). The percentage inhibitive efficiencies were not calculated because the final selection of the inhibitor was based upon the visual observation (where there was no change in surface appearance) and polarization results. In some cases, pieces of aluminum, high-strength steels, brass, and cast iron were suspended together in one electrolyte to check the effectiveness of inhibitors against interfering ions. Finally, the effectiveness of the inhibitor for metallic parts prone to galvanically coupled conditions was also examined. A galvanic couple was prepared as shown in Fig. 1. Pieces of aluminum, steel, brass, and cast iron were connected through a stainless-steel rod and individually bolted with stainless-steel nuts.

Low-cycle corrosion-fatigue tests [15] were conducted to determine the effectiveness of the inhibitor formulations in retarding crack growth. The rinse inhibitor--0.35% (w/o) borate + 0.05% nitrite + 0.1% nitrate + 0.01% silicate + 50 ppm phosphate + 30 ppm MBT--was used for this purpose. Compact-tension plane-strain fracture-toughness specimens, (Al 7075-T6) as shown in Fig. 2, were used to determine the crack-growth rate in the presence of uninhibited and inhibited tap water and saline solution. A detailed description of the corrosion-fatigue tests on high-strength aluminum alloys is given in Ref. [15]. Sinusoidal tension-tension cycling was used at a frequency of 0.1 Hz. All tests were performed at a maximum load of 5328N (1200 lbs) and a stress ratio, $R(\sigma_{min}/\sigma_{max})$, of 0.1. The specimens were initially precracked to a fatigue-crack length of ~ 2.54 mm (0.10 in.). The crack length was monitored using a double-cantilever-beam gauge and an amplifier-recorder system. The crack-opening displacement (COD) was recorded as a function of fatigue cycles.

In order to determine the crack lengths from COD data, compliance measurements were carried out for all aluminum alloys. Tests were conducted in air, and crack lengths were determined using optical and COD measurements simultaneously on the MTS machine. No significant differences were found in the COD/load and crack-length/load curves. The crack length, a, was calculated from the analytical compliance relationship [16]

$$a/w = 1.001 - 4.6695\ U + 18.460\ U^2 - 236.82\ U^3 + 1214.94\ U^4 - 2143.6\ U^5$$

where

$$U = \frac{1}{\sqrt{\dfrac{EB(COD_{Max} - COD_{Min})}{P_{Max} - P_{Min}}} + 1}$$

E is the Young's modulus, and P the stress. W and B are the dimensions indicated in Fig. 2. The stress-intensity values were calculated from

$$K = \frac{P}{BW^{1/2}}\ \frac{(2 + a/w)\ [0.886 + 4.64(a/w)] - 13.32(a/w)^2 + 14.72(a/w)^3 - 5.6(a/w)^4}{(1 - a/w)^{3/2}}$$

where B and W are the dimensions indicated in Fig. 2 such that B and a > 2.5 $(K_{IC}/YS)^2$, with K_{IC} being the fracture toughness and YS the tensile yield strength. The crack-length-vs.-number-of-cycles data were converted to fatigue-crack-growth rates (da/dN) using a computer program [16]. Seven to eleven data points were fitted to a second-order polynomial, and the derivative (da/dN) was then obtained for the middle data point. This process was then repeated over the range of data. The da/dN-vs.-ΔK curves were then constructed based upon test data of uninhibited and inhibited solutions.

Commercial inhibitor solutions and aerosols were obtained from the manufacturers or commercial vendors. Reagent-grade chemicals and distilled water were used to make solutions, with the exception of the use of tap water for typical hard-water simulation. The most aggressive solution used was an aqueous solution containing 0.1M sodium chloride to represent a highly contaminated rinse solution after multiple recycling in the Rinse Facility. Most of the tests were conducted in tap water (Wright-Patterson Air Force Base, Dayton, OH). Several tests were performed in the water obtained from the Automated Rinse Facility at MacDill Air Force Base in Tampa, FL. The analysis of the rinse water at MacDill is shown in Table 2.

RESULTS AND DISCUSSION

From the hundreds of polarization and immersion tests that have been conducted in this investigation, a number of representative results have been selected for discussion in this paper. It is important to understand that optimizing inhibitor formulations for aggressive environments such as 0.1M sodium chloride in water requires many more experiments than will be described here. Initially any new formulation was tested with Al 7075-T6; if the anodic-polarization curve looked encouraging (in terms of current density and the amount of passive region), the performance of the formulation was checked with high-strength steel and brass. It was found that aggressive environmental effects that were inhibitive toward the corrosion of high-strength aluminum alloys were generally protective toward other aerospace alloys such as high-strength steels. The converse of this, however, was generally not true.

Figure 3 shows the anodic and cathodic polarization of Al 7075-T6 and Al 2024-T3 in one of the inhibitor formulations. As expected, there is a small difference in the anodic current at the nose level. The difference is more apparent in the cathodic curve; although not clearly shown, the anodic part of the curve has a larger passive region for Al 2024-T3. These two results simply indicate that Al 2024-T3 is more effectively inhibited than Al 7075-T6, possibly due to the fact that Al 2024-T3 is more corrosion resistant than Al 7075-T6 under these conditions. The results of anodic polarization tests of Al 7075-T6 in Wright-Patterson Air Force Base tap water, distilled water, 0.1M NaCl, and one of the inhibitor formulations (0.35% sodium borate, 0.05% sodium nitrite, 0.1% sodium nitrate, 0.01% sodium metasilicate pentahydrate, 50 ppm sodium metaphosphate, and 30 ppm sodium salt of MBT) are shown in Fig. 4. It is interesting to note that nearly the same level of current density is providing the passivity for aluminum in both distilled water and the inhibited solution. However, the results of the long-time immersion tests show the difference in the corrosion rates of aluminum in these solutions (see Table 3).

Figure 5 shows the performance of the borax-nitrite-base inhibitor as compared to that of sodium nitrate, sodium dichromate, and one of the most promising commercial inhibitors screened in this investigation. The corrosion current extrapolated against the passive region is least for the borax-nitrite-base inhibitor; at the same time, better passivity is achieved by this formulation. This formulation was found to be effective in inhibiting the corrosion of high-strength steels, aluminum alloys, and copper-bearing materials such as brass.

Borates alone are not particularly effective as inhibitors except for perhaps a limited number of ferrous alloys in mild environments. Nitrites provide a degree of protection to iron and carbon steel in tap water similar to that provided by the chromates; however, higher inhibitor concentrations are required with increasing chloride content to protect against local corrosion [17]. A mixture of borate and nitrite, however, was found to be very effective in the corrosion inhibition of high-strength steels. The borax-nitrite system does not provide satisfactory inhibition to aluminum. Silicates, phosphates, and nitrites are the most commonly known passivators of aluminum. In addition silicates and phosphates [18] provide corrosion inhibition to iron and high-strength steels. The nitrates [19] are known to provide protection to aluminum and its alloys against attack by chloride ions. Hence, a mixture of borate-nitrite, silicate, nitrate, and phosphate in the proper concentrations should provide inhibition to iron, steel, and aluminum. Sodium mercaptobenzothiazole was added to the formulation due to the problems expected from the presence of copper ions in the Rinse Facility. The sodium salt of MBT is known [20] to provide inhibition to copper and its alloys. This explains the excellent inhibition provided to aluminum, brass, and steel by the rinse formulation developed in this study as shown by the anodic-polarization results in Fig. 5 and the immersion results in Table 3.

Generally the exact concentration of inhibitor needed depends upon the quality of the water, especially upon the chloride content. The breakdown of the passivity with increasing concentration of chloride ions is demonstrated in Fig. 6. The results show that up to 1000 ppm NaCl, the passive region still occupies nearly a 400-mV portion of the anodic curve and that the corrosion current remains the same. This establishes a conservative limit for effective use of this inhibitor in tap water, even in the presence of 500 - 600 ppm NaCl.

Extensive weight-loss tests were conducted to supplement the polarization experiments. Although these tests are time consuming, they have certain advantages over polarization tests, where small mistakes could result in erroneous conclusions. The results of several weight-loss tests are shown in Table 3, and the corrosion rates calculated represent the average values obtained from five to ten tests. The best results were obtained with the formulation of sodium borate, sodium nitrate, sodium nitrite, sodium metasilicate, sodium phosphate, and sodium salts of MBT which was found to be effective in inhibiting the corrosion of aluminum, copper, and steel in Tampa, FL, water (see Table 2). It is interesting to note the difference in corrosion rates of Al 2024-T3 and Al 7075-T6 when immersed in distilled water and inhibited tap water. According to the anodic-polarization curve, the passivity of aluminum is achieved both in distilled water and inhibited water at the same current-density level as that shown in Fig. 4. However, the long-time immersion test results show a corrosion rate of 0.34 - 0.57 mpy for Al 2024-T3 and 0.051 to 0.95 for Al 7075-T6 in distilled water from weight-loss measurements; no corrosion was detected in the borax-nitrite-base inhibitor solution. This illustrates the need for conducting weight-loss tests in parallel with fast screening polarization tests for adequate evaluation of inhibitor-formulation effectiveness. To expand the experimental variables of importance, some immersion tests were conducted where a) the solution was stirred, b) only the lower-half portion of the specimen was immersed, c) the specimen was intermittently immersed and dried, and d) the specimen was sprayed with the inhibitor solution. The performance of the borax-nitrite-based inhibitor was excellent in all of these situations.

The performance of this inhibitor was investigated in situations where localized attack, coupled with external stress, leads to catastrophic failures. A corrosion fatigue test closely simulates such conditions on a laboratory scale. Figure 7 shows the effect of the addition of a borax-nitrite-based inhibitor to the aqueous solution upon the crack-growth rate of Al 7075-T6 in the LT orientation. Reduction in the fatigue-crack-growth rate due to the addition of the borax-nitrite-based inhibitor was almost an order of magnitude. The addition of the inhibitor reduces the fatigue-crack-growth rates from those observed in distilled water, tap water, and sodium chloride to that observed in ambient air. The environmental enhancement of crack-growth rate has thus been eliminated by the action of the inhibitor system.

The borax-nitrite-based inhibitor with additions of nitrate, polyphosphate, metasilicate, and mercaptobenzothiazole was recommended for use in the Rinse Facility as a result of the research efforts in 1978. Experimental use commenced in the summer of 1978 with inhibitors added to the rinse water. In August of 1979 a full-scale test program to evaluate the use of an inhibited rinse was begun on F-4 aircraft stationed at MacDill Air Force Base, FL. The missions of these aircraft emphasize over-sea water exercises at low altitudes; MacDill Air Force Base itself is surrounded on three sides by salt water. In addition the Tampa industrial area contributes substantial suspended particulates and sulfur dioxide to the atmosphere. Thus, it is considered to be a prime area for conducting such tests for the use of automated rinsing to reduce contamination of surfaces and subsequent increased corrosion on operational aircraft. Twenty-five F-4 fighter aircraft were selected to use the Rinse Facility, and a second group of twenty-five F-4's not using the facility was designated as a control group. This test program is still underway, and it is planned that tracking of maintenance costs and corrosion damage will be completed within the next year.

Some problems have arisen with the maintenance of a discrete population of aircraft within the test group and the control group, since some aircraft have been transferred to other stations. It now appears, however, that at least one-half of both groups will be maintained at MacDill Air Force Base for a sufficient time to complete a two to three year test program. As far as the authors know, this is the first attempt to actually track maintenance costs in the use of aircraft rinsing facilities. The general observation has been that this practice is "beneficial," but no cost-effectiveness studies have been conducted.

A view of the Rinse Facility at MacDill Air Force Base is given in Fig. 8. The holding tanks for rinse water, major piping and pumping systems, return tanks, etc., are located underground. Only the control facilities are above ground. The inhibitors are added to a tank holding ~ 11,000 liters of water (~ 3,000 gallons). A forced-air system mixes the inhibitors to effect full desolution within about 1 min. after addition, and a conductivity bridge is used to monitor inhibitor concentration in the rinse water. When an aircraft passes over an induction coil on the runway, it triggers the rinse system to deliver ~ 560 liters of rinse water in a 15 - 20 sec. time period, pumping at ~ 2,250 liters/min. at the maximum point after startup. Water jets below the runway/taxiway surface direct water to various parts of the aircraft. An F-4 aircraft as it taxis through the facility is shown in Fig. 9.

The method of monitoring the rinse-inhibitor concentration by following the change in conductivity is shown in Fig. 10. Laboratory experiments have shown this to be a reliable and accurate method. The Rinse Facility provides for discharge of the effluent water periodically as contaminants build up and for the removal of oily water to appropriate disposal facilities. In actual practice, 100 - 200 liters of water are lost on the runway and not returned to the holding tanks after each aircraft rinse. Fresh water is added to the holding tank at this point, and tracking of the inhibitor concentration is essential in determining when additional inhibitors should be added. While this could be accomplished automatically, in the current test it is done manually. Recent experiments have indicated that the action of the rinse-inhibitor formulation may be improved by small additions of a surfactant material (in the parts-per-million level). This change in the rinse-inhibitor composition is planned for late spring of 1981.

CONCLUSIONS

Multifunctional nonchromate inhibitors have been developed for the USAF Automated Rinse Facility to reduce corrosion maintenance costs by removing corrosive contaminants from aircraft which operate in aggressive environments such as those encountered near the sea coast. These inhibitor systems are low cost, water soluble, nontoxic formulations which are effective against general corrosion, localized corrosion, and environmentally assisted crack growth under conditions of stress corrosion and corrosion fatigue.

Extensive polarization, immersion, and galvanic-coupling experiments have been conducted to determine the effectiveness of various inhibitor systems in aggressive media including solutions containing high chloride concentrations and the hard water used in the Rinse Facility.

A borax-nitrite-based inhibitor containing small additions of nitrate, silicate, phosphate, and mercaptobenzothiazole has been found to provide excellent corrosion protection for the high-strength aluminum and steel alloys used in aerospace applications and for the copper-bearing alloys used in electronic components and in parts of the Rinse Facility.

Environmental effects upon crack-growth rates of aluminum and high-strength steel alloys were eliminated--reducing the rates in corrosion fatigue as compared to those obtained in air.

A test program using these inhibitors is currently underway in the USAF Automated Rinse Facility at MacDill Air Force Base, FL. Tracking of maintenance costs and corrosion damage is being conducted to determine the effectiveness of the inhibited rinse in reducing corrosion costs.

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TABLE 1
INHIBITORS

A. GENERAL CONSIDERATIONS

1. Multifunctional
   - Cathodic
   - Anodic
   - Chloride Absorbers
   - Buffers
2. Solubility Range
3. Influence on Hydrogen Entry Rates
4. Toxicity
5. Cost

B. COMPOUNDS

1. Cathodic: Polyphosphate, Zinc, Silicate
2. Anodic: Orthophosphate, Chromate, Ferrocyanide, Nitrite
3. Combinations: Polyphosphate-Chromate
   Polyphosphate-Ferrocyanide
   Borax-Nitrite
   Benzoate-Nitrite
   Silicate-Chromate
4. Film Formers: Emulsified or Soluble Oils
   Octadecylamine
   Long-Chain Amines
   Alcohols and Carboxylic Acids

C. GENERAL CONSIDERATIONS

1. Stress Corrosion and Corrosion Fatigue
2. Special Environments
3. Long-Term Effectiveness
4. Method of Application

TABLE 2
CITY OF TAMPA - WATER DEPARTMENT
AVERAGE DAILY ANALYSIS OF FINISHED WATER

	Color Units	Total Hardness $CaCO_3$	Total Alkalinity $CaCO_3$	Calcium Hardness $CaCO_3$	pH Units	Resid. Chlorine	Temp °F
Max.	4	196	118	164	7.6	3.5	81
Min.	3	171	103	142	7.4	2.7	77
Average	3	181	110	154	7.5	3.2	79

June MONTHLY COMPOSITE
COMPLETE ANALYSIS
(Results expressed in milligrams per liter)

Calcium	Ca	61.6
Magnesium	Mg	7.00
Sulfates	SO_4	55.
Chlorides	Cl	57.
Fluorides	F	0.32
Sodium	Na	36.0
Potassium	K	3.2
Nitrates	NO_3	0.08
Silica	SiO_2	4.4
Manganese	Mn	0.0
Iron	Fe	0.08
Bicarbonates	HCO_3	136
Phosphates	PO_4	0.26
Aluminum	Al	0.30
Total Solids		350
Total Hardness	$CaCO_3$	180
Total Alkalinity	$CaCO_3$	112
Non-Carb. Hardness	$CaCO_3$	68
Ammonia-Nitrogen	NH_3	ND
L.A.S.	MBAS	0.03
Copper	Cu	0.03
Color	Units	3
Turbidity	Units	0.7
pH	Units	7.6
Temperature	°F	76
Sp. Conductivity	MMhos	425
B.O.D. (5 days at 20°C)		0.2

TABLE 3

IMMERSION TEST RESULTS

No. of Tests	Electrolyte	pH		Surface Appearance		Corrosion Rate (mpy)		Remarks
		Initial	Final	2024-T3	7075-T6	2024-T3	7075-T6	
5	Tap Water (WPAFB)	7.62	8.48	Stained; several pits.	Couple of oxide patches; several pits.	0.034 to 0.65	0.38 to 0.78	Should be inhibited.
5	0.1M NaCl in Distilled Water	6.95	7.50	Entire surface corroded; several pits.	Entire surface corroded; several pits.	1.38 to 1.98	1.54 to 2.4	Should be inhibited.
5	NALCO 39L (18cc/liter) in Tap Water	9.24	9.00	Looks as original.	Looks as original.	$< 10^{-4}$	$< 10^{-4}$	Very good.
3	Betz 545 (500 ppm) in Tap Water	8.83	8.42	Corners and edges badly pitted; surface fairly clean.	Entire surface dark; several pits.	0.017 to 0.063	0.028 to 0.054	Poor.
5	Calgon Inhibitor CS (4000 ppm) in Tap Water	8.90	8.80	Light tinted scale all over; no visible pits.	Light tinted scale all over; no visible pits.	0.067 to 0.088	0.083 to 0.092	Poor.
3	1% Sodium Dichromate in Tap Water	5.80	5.80	Surface looks as original.	Surface looks as original.	$< 10^{-4}$	$< 10^{-4}$	Very good.
3	0.1% (Sodium Metasilicate + Sodium Polyphosphate) in Tap Water	8.64	8.45	Surface looks as original.	Surface looks as original.	$< 10^{-4}$	$< 10^{-4}$	Very good.
8	0.35% Sodium Borate + 0.05 Sodium Nitrite + 0.1 Sodium Nitrate + 0.01 Sodium Silicate + 50 ppm Polyphosphate + 30 ppm MBT in Tap Water	8.78	8.84	Surface looks as original.	Surface looks as original.	$< 10^{-4}$	$< 10^{-4}$	Excellent.

Figure 1. Galvanic Couple.

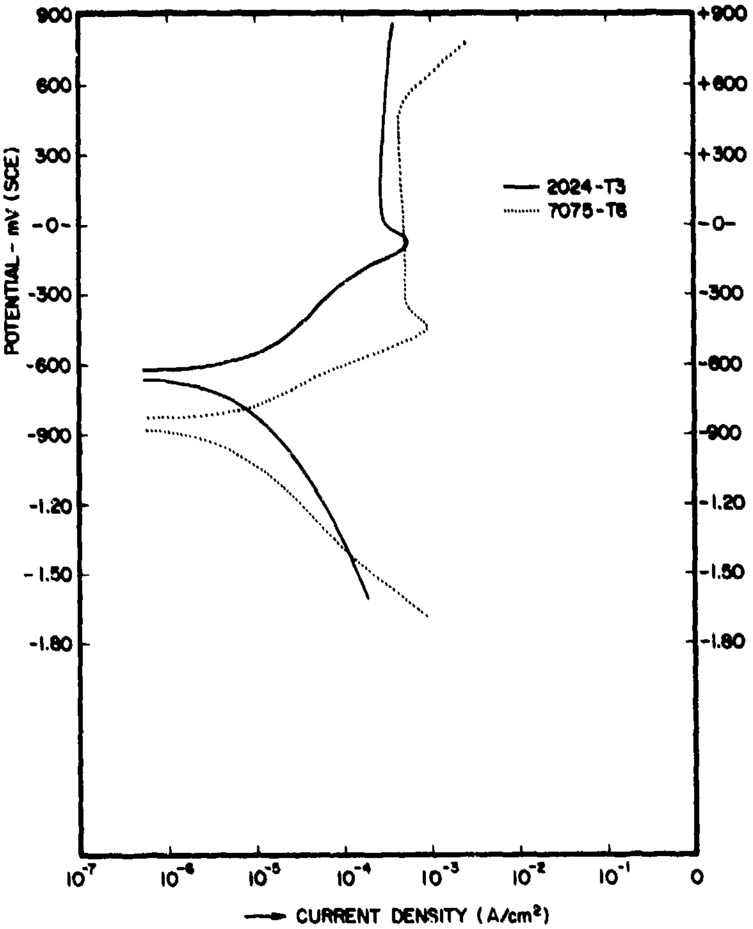
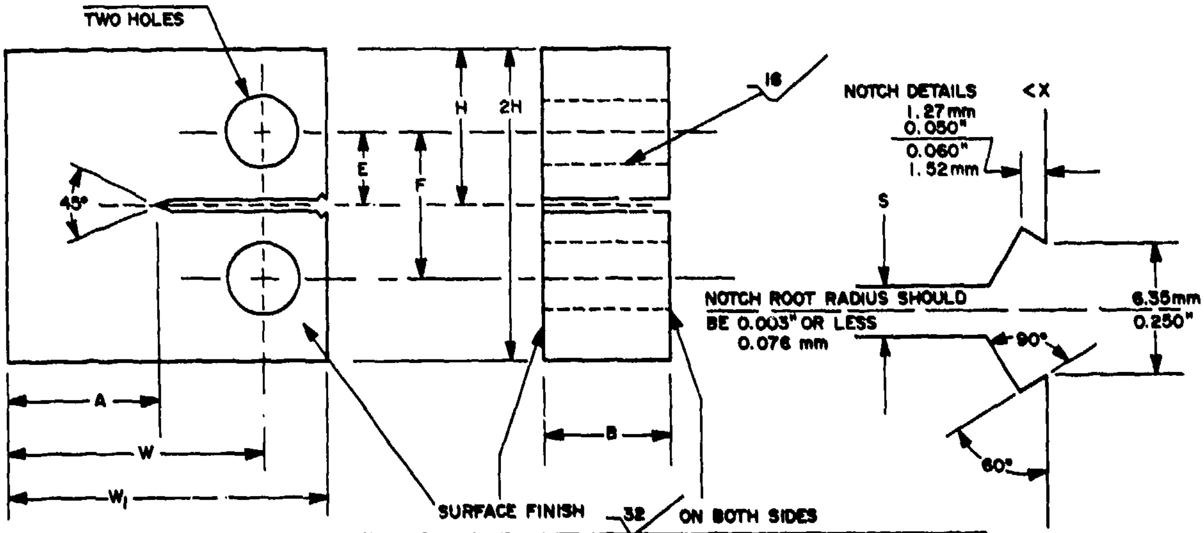


Figure 3. Anodic and Cathodic Polarization Curves for Al 2024-T3 and Al 7075-T6 in an Inhibited Solution.



MATERIAL	B	A	W	W_1	S	E	F	H	D
ALUMINUM	25.4mm	29.2mm	50.8mm	63.5mm	2.36mm	13.97mm	27.94mm	30.48mm	12.7mm
STEEL	19.05mm	22.22mm	38.10mm	47.62mm	1.90mm	10.46mm	20.95mm	22.86mm	9.52mm

Figure 2. Compact-Tension Specimen.

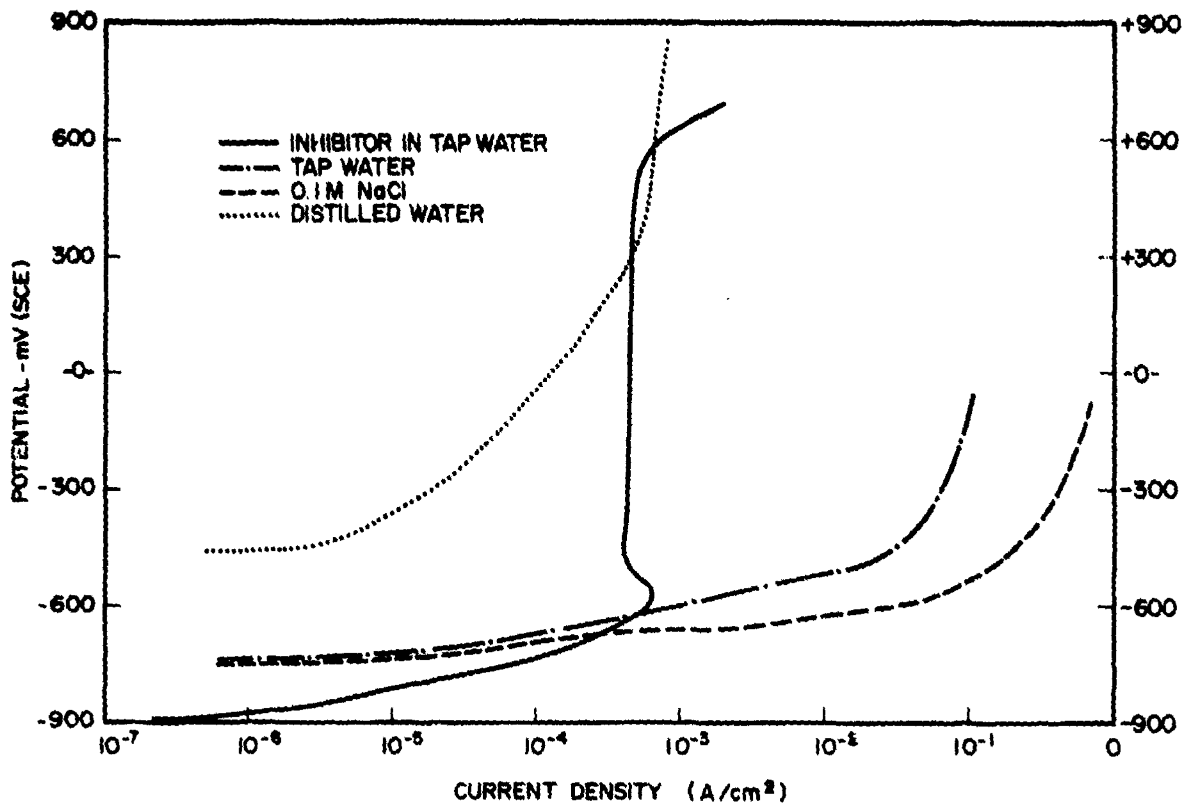


Figure 4. Anodic Polarization Curves for Al 7075-T6 in Tap Water, Distilled Water, 0.1M NaCl, and Inhibitor.

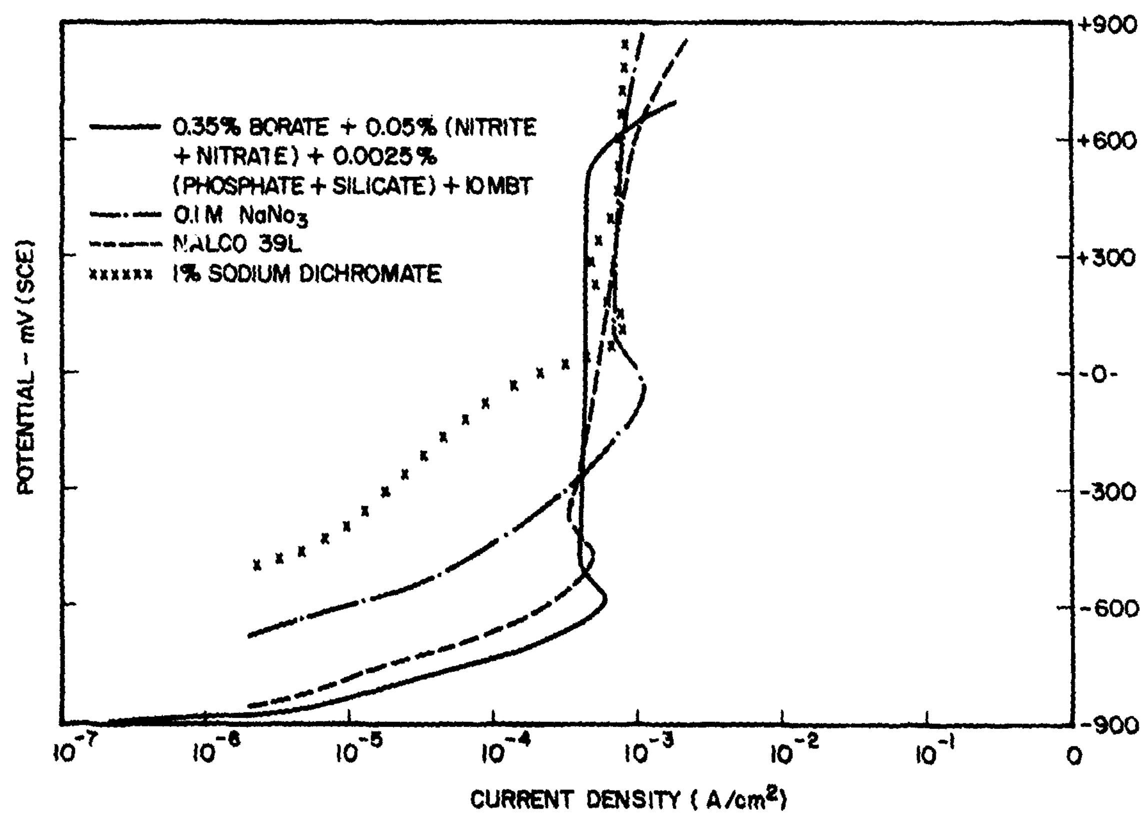


Figure 5. Anodic Polarization Behavior of Al 7075-T6 in Different Inhibitors.

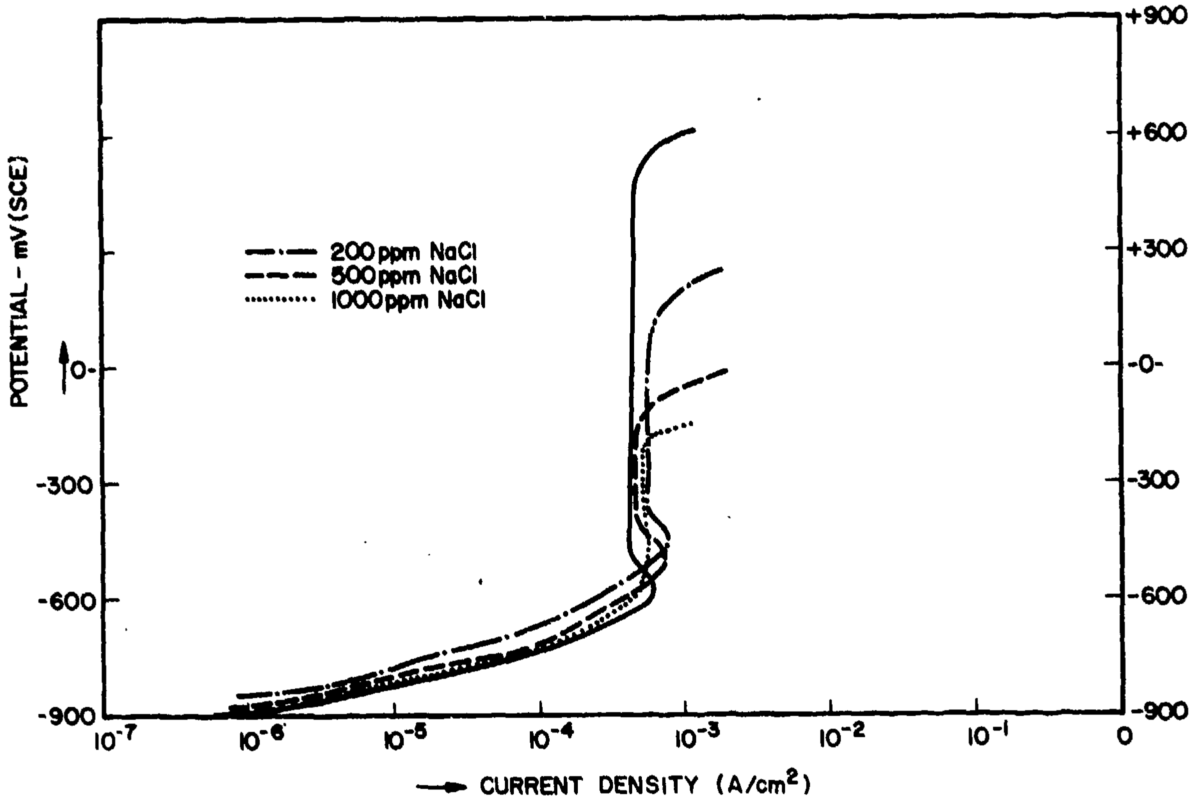


Figure 6. Effect of Increasing Chloride Concentration Upon the Pitting Behavior of Al 7075-T6 in an Inhibited Solution.

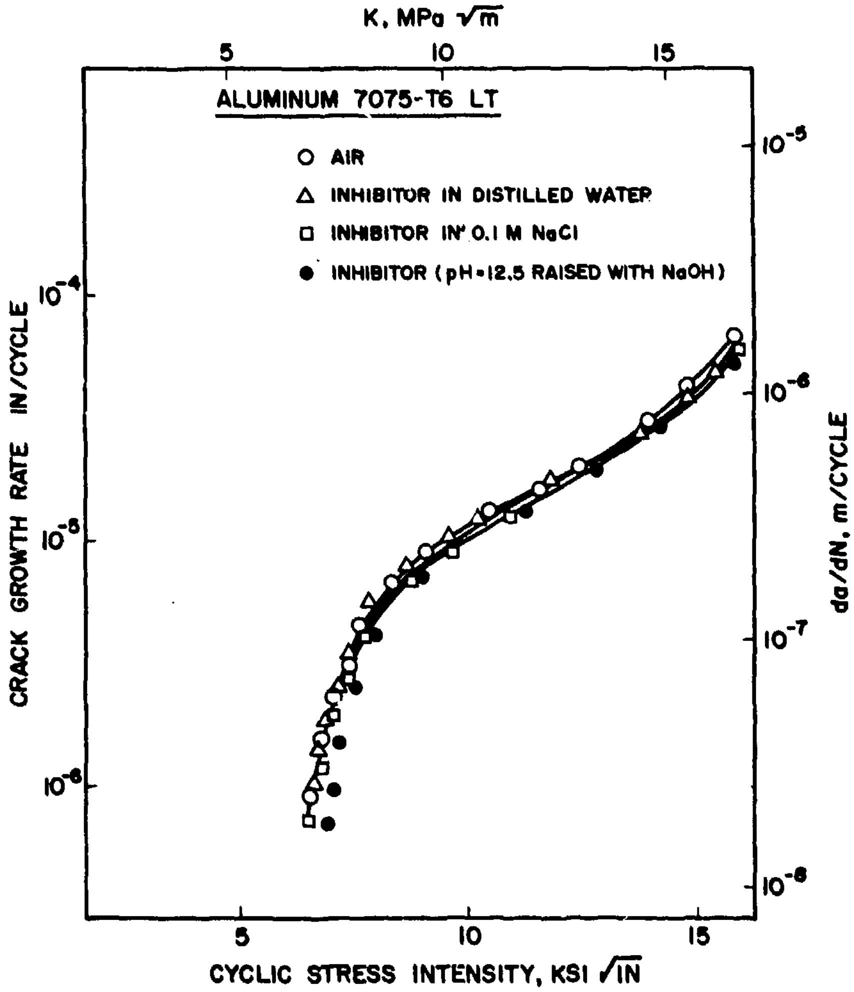


Figure 7. Effect of Inhibitor Upon Corrosion Fatigue of Al 7075-T6 LT.

Figure 8. View of the USAF Automated Rinse Facility.

Figure 9. F-4 Aircraft Taxiing Through the Rinse Facility.

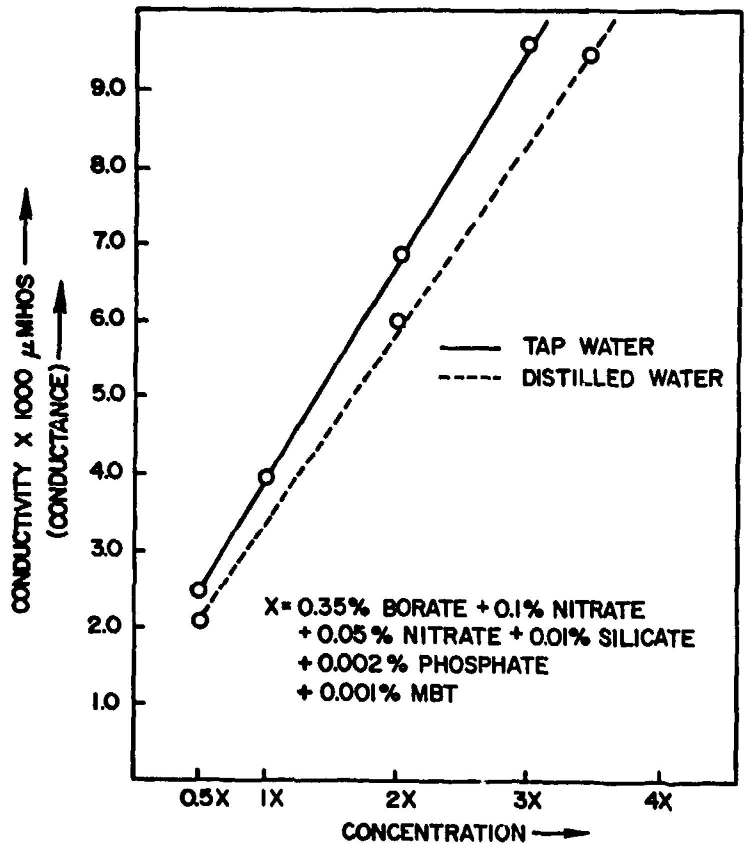


Figure 10. Calibration Chart of Conductivity as a Function of Inhibitor Concentration.

CORROSION IN NAVAL AIRCRAFT ELECTRONIC SYSTEMS

Irving S. Shaffer
Naval Air Development Center
Warminster, Pennsylvania
USA

SUMMARY

Naval aircraft electronic equipment suffer frequently from the effects of moisture and corrosion. The critical design features which have led to excessive susceptibility to these failure modes are described. Several examples are cited of inadequately protected equipment having been located in aircraft installations where they are subjected to repeated moisture intrusion during rainstorms, low level flights over water and high pressure fresh water washdowns. The specific deterioration effects that occur on the various components that make up the avionic systems are presented. Maintenance data summaries are included to denote further the corrosion problem severity. Corrective measures in design, testing and maintenance are discussed.

INTRODUCTION

In today's sophisticated naval aircraft the performance of the avionic systems is critical to the overall mission capability. Recently,(1,2,3,4,5) however, corrosion has become increasingly identified as a major concern in the reliability of electronic equipment. It has been stated (6) that the effects of moisture and corrosion are the greatest causes of failure in electronic systems after thermal and power overloads. High corrosion failure rates indicate that the equipment is not being designed for or tested in an environment similar to that in which it will be employed. As a result, operational conditions are causing failure modes that were neither considered during design nor discovered and eliminated during testing. On-site surveys (7) of front line combat aircraft have concluded that the significant design factors contributing to corrosion are; poor resistance to moisture intrusion, numerous matings of dissimilar metals, and fluid conduits within the airframe.

MOISTURE AND FLUID INTRUSION

Avionic equipment, whether internal or external to the aircraft, on the repair bench or in storage can be susceptible to conditions such as changing temperatures and pressures, varying humidity, dust, dirt and industrial pollutants in the atmosphere. In addition the Navy's aircraft carrier environment exposes sensitive electronics to a combination of moisture, acidic deposits from stack gases, jet engine exhaust, and salt spray. The equipment that suffers the most from these environmental effects are those mounted external to the airframe such as; antennas, electronic countermeasure pods, photographic pods and lights. There are many situations where avionic devices are installed behind doors and panels that leak during flight through rainstorms or on low level flights over water. If the integrity of the airframe is less that perfect during rainstorms, fresh water washdowns can be equally hazardous. High pressure washing units deluge the aircraft with tremendous amounts of water in a short time. Two prime examples of susceptibility to this condition are the clamshell doors on helicopters and radomes on fixed wing aircraft. These doors and radomes leak like sieves when the gaskets become worn or damaged. In addition, exhaust fan inlet ducts, ram air cooling ducts, and vapor exhaust ports that are designed without a self-sealing mechanism become excellent access areas for water and moisture intrusion. Helicopters, in particular, are designed with minimal consideration for the operational environment. There are numerous flight scenarios that require cockpit windows and cabin doors to be open. Numerous cases exist where control boxes and communication equipment are mounted aft, or below, the door and window openings, allowing water to enter the equipment. Figure 1 provides an excellent example of the effects of water intrusion. This severely corroded power supply subassembly, mounted in the turtle back area behind the cockpit on the A-6 aircraft, was victimized by frequent water intrusion soakings.

The external bulkhead electrical connectors, external wire and cable runs, antennas, control linkages and other such areas where the shell of the fuselage is penetrated can become potential sources for moisture and fluid intrusion. The list of airframe integrity problems relative to water intrusion during flight is extensive.

Besides the water intrusion problems occurring during flight, airframe integrity is compromised also in the maintenance periods. Many additional problems are encountered while aircraft are parked on the flight deck. In general during the majority of their ground time aircraft are opened up or unbuttoned to some degree. Figure 2 shows an A-7 with its canopy, radome and access panels open on the flight deck as maintenance is being performed. The need for canopies to be open during certain maintenance functions produces situations where rain and salt-spray may soak cockpit avionic components. The removal of a waveguide or a doppler or ADF antenna from the aircraft exposes the supporting electrical connectors, harnesses and cables to the environment. The troubleshooting of radars on fighter and attack aircraft may require the radomes to be open for hours on end, continually exposing the equipment to rain and salt-spray. The same is true during troubleshooting in avionic bays and compartments.

Environmental control systems add another insidious facet to the overall problem of moisture and fluid intrusion. These systems are not operated on a round the clock basis. The avionics are protected while the environmental control system is supplying conditioned air during flight and then are exposed to a completely different and harsher environment during the more extensive time spent on the ground. The equipment becomes particularly prone to water condensation when the aircraft after setting for long periods of time on a hot carrier deck undergoes rapid changes in temperature at flight altitudes. Moisture condenses on cooled surfaces, during flight, and then is trapped until natural evaporation mechanisms take over during down time.

The problems of moisture and fluid intrusion are critical to the overall avionic corrosion considerations. The avionic equipment may be designed under the premise that in service it will be enclosed or in some matter protected from changing climatic conditions when, in fact, the water intrusion caused by maintenance and airframe integrity problems may put the unit in a literal rainstorm.

MOISTURE AND FLUID CONDUITS

After moisture or fluids enter an airframe or avionic compartment it may follow a natural conduit directly into a sophisticated piece of avionic equipment. Hydraulic and fuel lines, control surface linkages, oxygen lines, waveguides, structural stringers and electrical wire/cable runs act as natural conduits to moisture and fluids. It is common to find that antenna and radars mounted in the lower fuselage are adversely affected by moisture intrusion which runs down the antenna coaxial cable and/or waveguide that carry the signals to and from the equipment. As these cables and waveguides pass through deck plates and bulkheads, where water is present, they act as conduits carrying the fluid into the connectors attached to the equipment. In one case the pilot's relief tube is routed along a radar waveguide, through the deck plates, into the lower fuselage, and directly onto the radar housing.

DISSIMILAR METALS

Almost all corrosion that occurs on electronic equipment is similar to that which occurs on larger structures. There are of course some types of corrosion which are unique to electronics equipment, but this is because some of the materials which cause such corrosion are unique to the electronics industry. Metals never considered for use in airframe structures are used widely in the manufacture of avionic equipment. Some of the rarer metals are found in transitors, miniature and microminiature circuits and integrated circuits. The following list indicates the uses made of some of the different alloy systems in the construction of various electrical and electronic components:

1. Iron and steel (ferrous alloys) are used as component leads, magnetic shields, transformer cores, brackets, racks, and general hardware.

2. Aluminum and aluminum alloys are widely used in avionic systems as antennas, structures, chassis, supports and frames (radar).

3. Magnesium alloys are used extensively throughout avionic systems as antennas, structures, chassis, supports, and frames (radar).

4. Stainless steel is used for mounting racks, brackets and hardware.

5. Copper and copper-based alloys are generally used in avionic systems as contacts, springs, leads, connectors, printed circuit board lands and wire.

6. Cadmium is used as a coating to protect ferrous hardware, such as bolts, washers and screws in contact with other metal.

7. Nickel and tin-plating are used for protective coatings and compatability purposes. The use of tin in solder is a well-known application; however, tin-plating is also common on RF shields, filters, crystal covers and automatic switching.

8. High purity electrodeposited gold has wide application in electrical connectors, printed circuited runs and edge connectors, miniature coaxial connectors, semi-conductors, leads and contacts.

9. Silver is used normally as a plating material over copper in waveguides, miniature and microminiature circuits, wires, contacts, high frequency cavities, tank circuits and RF shielding.

Considering that avionic components are constructed of the foregoing variety of metals, and many others, it is evident that there are a great many galvanic couples or cells in such equipment. Many components have areas of contact between several dissimilar metals. It, therefore, seems obvious that the potential for galvanic corrosion is an inherent design characteristic. However, the need for many of the dissimilar metal couples that are created in much of the equipment cannot be justified. As examples cited later will indicate there often is an apparent total disregard for electrochemical compatibility in metal selection for avionic equipment.

THE EFFECTS OF CORROSION ON AVIONIC COMPONENTS

The avionic systems on aircraft are not isolated "black boxes" sealed against the environment. There are many components, relays, terminal boards, circuit breaker panels, switches, lights, etc. that make up a complete system. In addition, a sophisticated aircraft may contain miles of wire and coaxial cables and hundreds of electrical connectors. Corrosion attack on the various elements that make up the total avionic systems can create numerous problems in relation to reliability and maintainability. Table 1 summarizes the effects of corrosion on avionic components.

Undoubtedly, the most corrosion prone component in avionics equipment is the antenna. Antenna and antenna mount corrosion is especially severe in lower fuselage bilge area installations. Automatic direction finder (ADF) and doppler antennas and numerous blade antennas are usually mounted in these areas. Water entrapped in the bilges forms puddles around the antennas. This entrapped water serves as an electrolyte between the antenna housing and aircraft skin. Fiber gaskets act as sponges, holding moisture between the interfaces. A much worse condition occurs when conductive gaskets impregnated with graphite, silver or copper are used. These gaskets, placed between the aluminum skin and the aluminum antenna to enhance conductivity, create a galvanic corrosion condition that not only precludes the enhanced conductivity, but causes the antenna to require frequent replacement.

Electromechanical devices such as switches, relays, potentiometers, motors, generators and synchro parts tend to corrode during storage or periods of non-use. The principal causes of malfunction (8) are dust, condensates, and resultant corrosion products such as oxides and organic contaminant films. Friction tends to keep the critical surfaces clean during operation. Insulating films form during non-use and prevent start-up of equipment.

Thin film and integrated circuits are susceptible to electrolytic corrosion (9) in the presence of moisture and electrical bias and to galvanic corrosion when dissimilar metals are in contact. Printed circuit boards suffer primarily from electrolytic corrosion, although tarnishing of the contact fingers is also important. Separable contacts develop excessively high or unstable contact resistances due to tarnishing of the plating or to corrosion of the substrate at the bases of pores in the plating and the transport of the corrosion product over the contact surface. Given the narrow springs between conductor paths and appreciable applied voltages, electrolytic corrosion is of real concern. Moisture can reach the surface of a device by diffusion through a cover coat or ingress through a faulty seal. Failure of a device results either from the development of an open circuit or from a short circuit caused by the redeposition of the anodic dissolution product at the cathode. The multilayer metallizations used in thin film and and integrated circuits are subject to galvanic corrosion (10) at sites where the more active metal is exposed to the environment, such as pores and edges. While printed circuit boards are usually conformal coated, in many cases, as Figure 3 clearly shows, circuit boards have been placed in service without any protection and have corroded severely.

Considering the large number of electrical connectors in a modern aircraft, connector water and corrosion damage cause some of the most costly repairs in the Navy's avionic maintenance business. The major problem with connectors is that of water intrusion or fluid contamination that causes corrosion, insulation damage, short circuits, fire, signal loss or intermittancy, wire failure through insulation and/or connector damage and grommet seal swell or shrinkage. These problems can and do cause equipment failures and safety hazards which, in turn, affect fleet readiness and operability.

The following electrical and coaxial connector corrosion problems are considered commonplace in naval aircraft:

1. Connector shell corrosion occurs when protective finishes are damaged and expose the base metal to the environment. It has been found that visual inspection of the outer surface of connectors is not always a good indication of their condition. Many connectors with an acceptable outward appearance are in fact heavily corroded internally and are impossible to uncouple without component destruction. The use of a thin electroless nickel plating over 6061 aluminum on connector shells has caused serious corrosion problems on some of our newest aircraft. Cracks develop in the nickel plating and when the surface is wet a galvanic cell is created with the aluminum corroding sacrifically. Figure 4 illustrates the effects of this galvanic corrosion on two coaxial connectors.

2. Electrical connectors that are externally mounted in the air stream are degraded by erosion of the external protective coatings with subsequent corrosion of the base metal.

3. Electrical and coaxial connectors mounted vertically are susceptible to water intrusion through the rear section when attaching cables do not contain a drip loop and serve as fluid conduits. Figure 5 exemplifies the dramatic effect of fluid conduit associated corrosion on vertically mounted connectors.

4. Bayonet type electrical and coaxial connectors mounted vertically are susceptible to degradation due to fluid entrapment around the base of the connector from standing water and/or hydraulic fluid.

5. Externally mounted electrical connectors hidden by fairing covers are prone to extensive corrosion damage because they are not visible for routine inspection and, therefore, timely corrective action.

6. Vertically mounted external electrical connectors on the upper fuselage transmission area of helicopters are susceptible to water entrapment at the base and rear of the connectors.

7. Supposedly environmentally sealed connectors in the engine, transmission, constant speed drive and hydraulic compartments are subject to damage of the environmental seal by hydraulic fluid, fuel and cleaning solutions. Numerous connectors in these areas are potted to eliminate this problem.

8. High density environmental electrical connectors are subject to seal damage and loss of integrity when maintenance personnel replace pins with extraction tools.

Cockpit and cabin areas are exposed to moisture intrusion through the canopy opening, cabin doors and windows. Most control boxes are susceptible to corrosion damage internally, especially those exposed to direct water impingement. Figure 6 shows such a corrosion situation. Corrosion can be seen around connecting pins, handles and hardware. Figure 7 provides a view of the internal damage to the box. Proper sealing of the box cover could have probably minimized the corrosion attack.

The backs of instrument panels are normally hidden from view. The numerous bimetallic couples and difficulty of inspection result in considerable corrosion damage. In the case of helicopters, the emergency ram air cooling ducts create an additional corrosion problem on instrument panels. All aircraft consoles use dissimilar metal fasteners, screws and nut blocks to secure instruments, thus creating galvanic couples. Figure 8 illustrates the type of instrument panel corrosion that occurs.

Circuit breakers, relay racks, and terminal boards also are prone to corrosion due to the dissimilar metals construction and exposure to moisture intrusion. Circuit breaker panels mounted in the overhead of helicopters are especially susceptible to water intrusion. Water enters through skin seams, windscreen edges and through upper fuselage skin penetrations for actuators, cables, etc. The water migrates onto the back of the circuit breaker panels, via cable conduits, and initiates the corrosion process with little change of visual detection until it is too late.

Radar waveguides, couples and joints are susceptible to corrosion damage due to moisture intrusion and dissimilar metal couples. When water runs along a waveguide it causes corrosion attack at the waveguide couples and joints, and without good preventive measures, may enter the waveguide flange causing serious degradation of the signal. The pressurized waveguide appears to be the best design to preclude these problems because the pressurization loss is an immediate warning of loss of integrity.

Avionic equipment shock mounts, racks and associated hardware are normally constructed of dissimilar metals and are relatively inaccessible for inspection and timely corrosion control. Associated with this problem is the bonding strap. Normally the bonding strap is used to bond the rack, shockmount, or an actual piece of equipment electrically to the airframe. The washers, screws and bonding straps usually create a dissimilar metal or a galvanic couple. The slightest amount of corrosion at any point of bonding (where dissimilar metals come in contact) can cause electromagnetic interference (EMI).

This problem is especially critical in the sophisticated avionic systems found in the more modern aircraft.

Lighting system failures due to corrosion run high during shipboard operations where the light and its associated plug are susceptible to the harsh salt-air environment. The slightest moisture intrusion creates a corrosion product between the bayonet-type bulb base and socket creating a loss of electrical contact (or ground). This problem is prevalent in all external light systems such as wing lights, formation lights, approach lights, etc.

MAINTENANCE DATA DOCUMENTATION

In electronics equipment, corrosion can be of such an insidious nature that its presence goes largely undetected until premature failures occur. An accurate assessment of the problem has been difficult to make since even after failure the corrosion causes often have not been properly recognized and reported. The documentation that is available does affirm the seriousness of corrosion in avionics. A summary of Navy maintenance data for various avionic systems installed on several different front line aircraft types is provided in Table 1. The data indicates a surprising number of discrepancies that were corrosion related. Considering all systems analyzed, it appears according to the data, that approximately 31% of all maintenance actions of these Navy avionic systems are corrosion related.

The "total maintenance actions sampled" is the aggregate of all discrepancies documented against the various systems sampled over a six month period from January through June of 1978. The "range of corrosion corrective maintenance" is the range (in percentages) from the lowest to the highest. The "average corrosion corrective maintenance" is the average corrosion discrepancies as a percentage of the total maintenance actions, less the "no defect" maintenance actions. Many reported discrepancies are designated as "no defect" because upon troubleshooting no malfunction can be found in the system. It has become apparent that many of these reported "no defect" discrepancies are caused by slight corrosion or the presence of moisture in a connector. The discrepancies disappear when the connectors are parted and then remated.

In Table 2 the "average no defects is the average "no defects" (no malfunction) as a percentage of the total maintenance actions. It is interesting to note the relationships of the corrosion and "no defect" items. Flight instruments show a 27% average corrosion corrective maintenance and 28% average "no defect" level. The positioning of flight instruments in the aircraft make them prime candidates for moisture intrusion. Many of these instruments could have failed due to corrosion or moisture in the connectors. The same problem could apply to light systems, control boxes, angle-of-attack systems and avionic equipment (black boxes).

CORROSION PREVENTION

When an avionic corrosion prevention/control program was established by the Naval Air Systems Command, a major emphasis of the program became the preparation of a Fleet maintenance manual. The lack of preventive maintenance guidelines had been recognized as a contributing factor for the high maintenance requirements for airborne electronics. In May 1978, NAVAIR 16-1-540, Avionic Cleaning and Corrosion Prevention/Control Manual, was issued to the Fleet. The manual provides instructions for inspecting for and recognizing corrosion in its early stages and identifies materials and procedures necessary for cleaning and corrosion control.

A prototype cleaning facility was established to evaluate the effectiveness of various cleaning methods for avionics equipment. The results of this study determined the optimum types of cleaning and corrosion removal equipment to be supplied to the maintenance activities for use on avionics.

A water displacing corrosion preventive compound was developed specifically for electronics equipment. The material, available under MIL-C-0081309, Type III, forms an ultra thin tacky (soft) film that is designed so that it is displaced by the action of a sliding electrical contact, yet the film is self-healing (reforms) in non-contact areas after displacement. The resultant lack of disruption to DC continuity through the male/female type of connections due to a MIL-C-81309, Type III film has been well established. (11,12,13)

Since the best and ultimately least expensive time to stop corrosion is at the design stage, a new program was initiated to develop a designers' guide for avionic corrosion prevention and control. This guide will identify critical design features, structural configurations, materials, material combinations and inadequate corrosion protection methods that have led to poor reliability and high maintenance requirements for avionic equipment placed in the Navy's severe operating environment. This guide is intended to provide an awareness of the corrosion problems that develop on the Navy's equipment and provide design methods that can be used to avoid or minimize them. It will not be the intent of this guide to dictate design criteria, but to document current corrosion problems so that they may be considered and avoided in the future.

Another current program that could have significant impact on future design is the development of a corrosion test method for avionic equipment. The purpose is to develop a test method that can be used as a qualification test to reveal areas of inadequate corrosion protection of new equipment and also be used to evaluate corrective measures for solving corrosion problems on equipment in service. The approach has been to formulate a test method that simulates service failures. Ideally the test environment should reduce the time required for failure initiation without altering the failure mechanism.

CONCLUSIONS

Corrosion and environmental degradation being natural phenomena will never be eliminated, but it is reasonable to expect that the problems that do develop in the avionics systems in the future can be less severe and better controlled that those presently being encountered. However, this goal can be achieved only through an aggressive technological effort directed towards the understanding of failure mechanisms, development of new improved corrosion control materials and methods, and the prudent utilization of innovative protection technology in the design, manufacture and service life of the avionics equipment.

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Table 1. Effects of Corrosion on Avionic Components

COMPONENT	FAILURE MODE
ANTENNA SYSTEMS	Shorts or changes in circuit constants and structural deterioration.
CHASSIS, HOUSINGS, COVERS, AND MOUNTING FRAMES	Contamination, pitting, loss of finish and structural deterioration.
SHOCK MOUNTS AND SUPPORTS	Deterioration and loss of shock effective-ness
CONTROL BOX MECHANICAL AND ELECTRICAL TUNING LINKAGE AND MOTOR CONTACTS	Intermittent operation and faulty frequency selection.
WATER TRAPS	Structural deterioration.
RELAY AND SWITCHING SYSTEMS	Mechanical failure, shorts, intermittent operation and signal loss.
PLUGS, CONNECTORS, JACKS AND RECEPTACLES	Shorts, increased resistance, intermittent operation and reduced system reliability.
MULTI-PIN CABLE CONNECTORS	Shorts, increases resistance, intermittent operation and water seal deterioration.
POWER CABLES	Disintegration of insulation and wire/ connector deterioration.
DISPLAY LAMPS AND WING LIGHTS	Intermittent operation, mechanical and electrical failures.
WAVEGUIDES	Loss of integrity against moisture, pitting, reduction of efficiency and structural deterioration.
RADAR PLUMBING JOINTS	Failure of gaskets, pitting and power loss.
PRINTED CIRCUITS AND MICROMINIATURE CIRCUITS	Shorts, increased resistance, component and system failures.
BATTERIES	High resistance at terminals, failure of electrical contact points and structural deterioration of mounting.
BUS BARS	Structural and electrical failures.
COAXIAL LINES	Impedance fluctuations, loss of signal and structural deterioration of connectors.

Table 2. Maintenance Data Summary

System	Total Maint. Actions Sampled	Range of Corrosion Corrective Maint.	Average No Defect	Avg. Corrosion Corrective Maint.
Light	4899	5-21%	12%	11%
Wiring	2192	6-80%	10%	42%
Power Supply	179	35-88%	4%	63%
Flight Instruments	1308	5-67%	28%	27%
Control Boxes	1980	9-38%	31%	23%
Pitot System	368	15-73%	7%	44%
Antennas	3359	0-100%	14%	32%
Avionic Equipment (Black Boxes)	2265	3-47%	35%	23%
Angle of Attack	400	18-68%	48%	35%

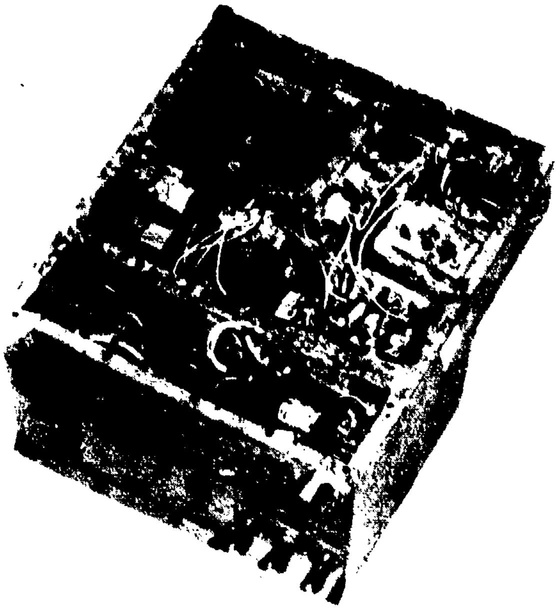


Figure 1. Corroded A-6 Power Supply Subassembly

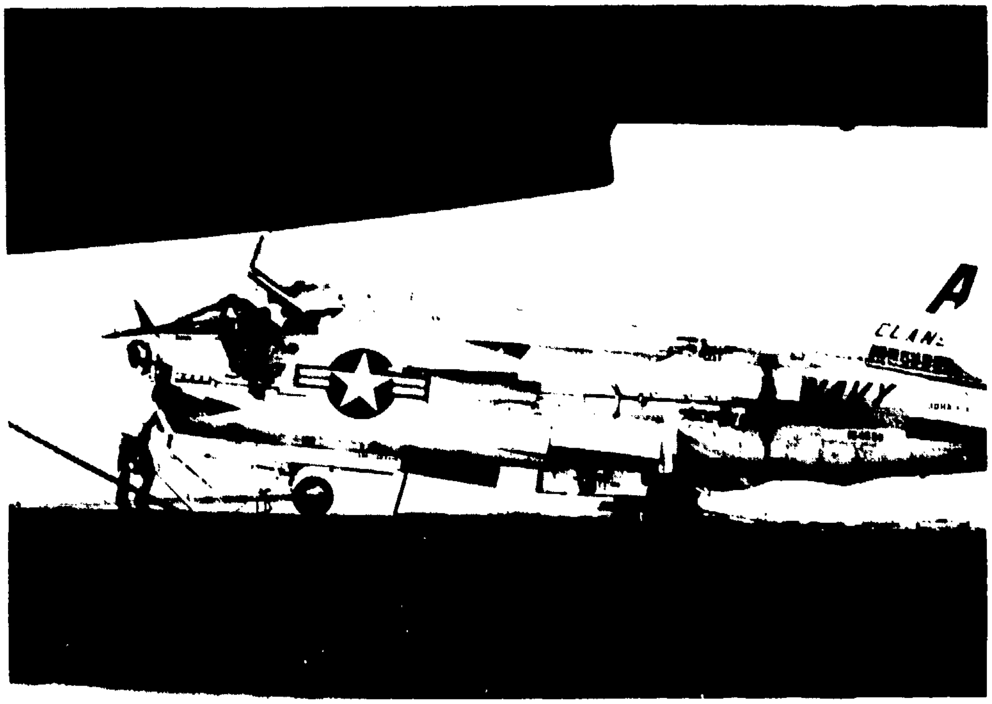


Figure 2. Aircraft Maintenance Being Performed on the Flight Deck

Figure 3. Results of Corrosion on Printed Circuit Board Circuit Runs

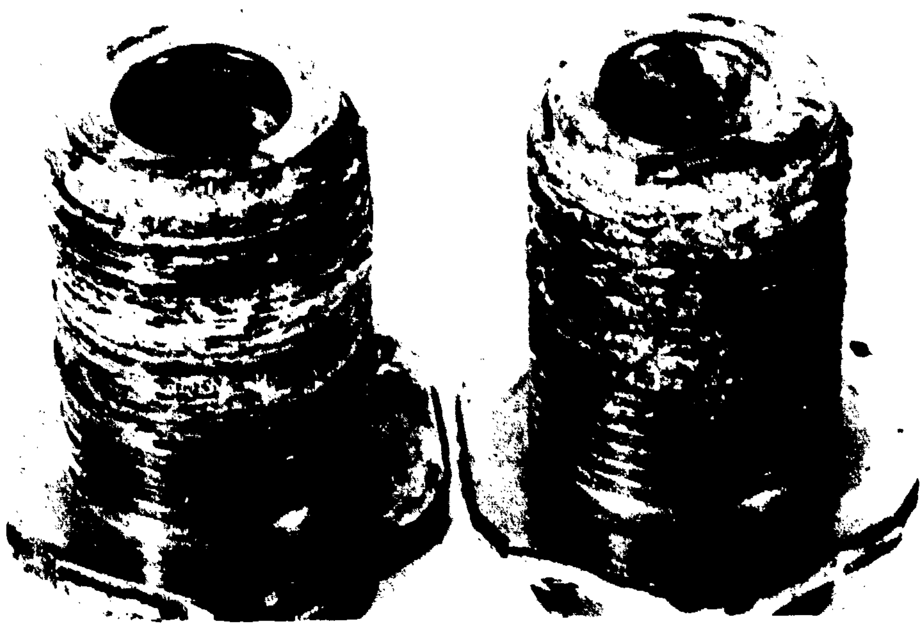


Figure 4. Galvanic Corrosion of Nickel Plated Aluminum Coaxial Connectors

Figure 5. Corroded A-6 Aircraft Vertically Mounted Circular Connectors

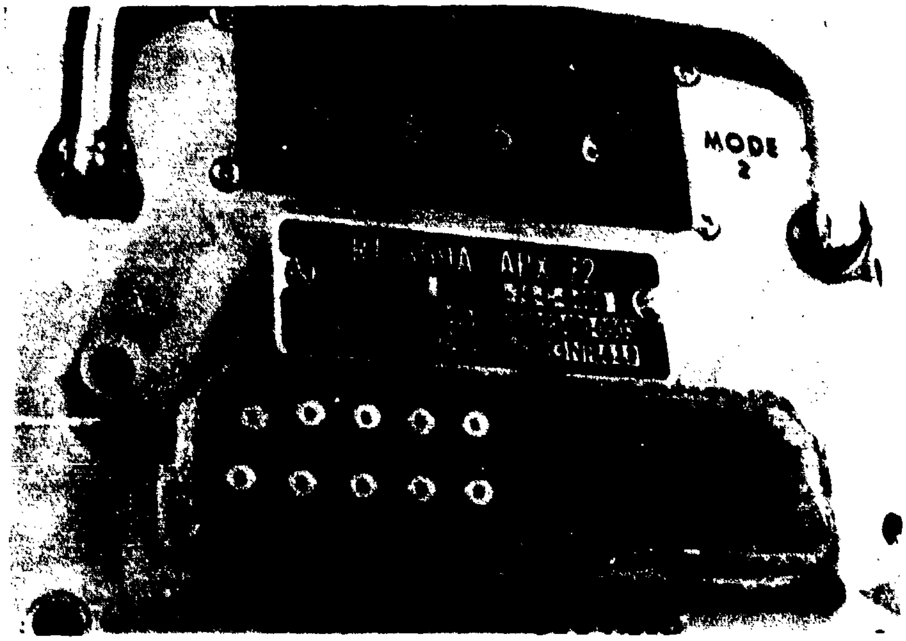


Figure 6. Corrosion Damage on Avionics Control Box

Figure 7. Internal View of the Gear Shown in Figure 6

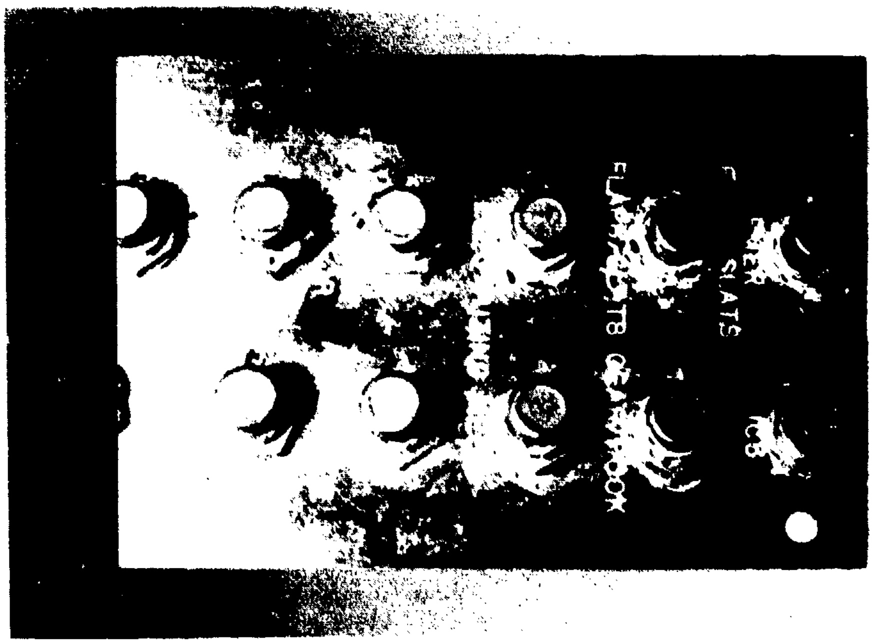


Figure 8. Results of Corrosion on Circuit Breaker Panel

CORROSION PROTECTION SCHEMES FOR AIRCRAFT STRUCTURES: SOME EXAMPLES FOR THE CORROSION BEHAVIOUR OF AL-ALLOYS

by

Dr Henri Lajain
VFW GmbH, Postfach 10 78 45
2800 Bremen 1
Germany

1. INTRODUCTION

Aircraft are subjected to many different loads so that the surface protection must be adjusted to the different corrosion effects that are to be expected. Consequently and especially in view of the required long service life of aircraft, the following requirements must be imposed with regard to the performance and quality of the surface protection:

1. The potential differences of the materials used are to be kept as low as possible, i.e. constructive measures must be taken.

2. Prevention of any local element activity by providing insulating protective coatings, i.e. by preventing a current.

3. Inhibition by providing cover layers (e.g. chromate passivation).

4. Introducing layers which act as so-called sacrificial anodes.

This paper gives a summary of the main groups of surface protection procedures frequently applied. In addition, some examples are given on the corrosive behaviour of aluminium alloys. To conclude the paper, information is given on novel non-destructive test methods serving to recognize corrosion within the scope of aircraft maintenance.

2. SET-UP OF THE SURFACE PROTECTION

The possibilities of corrosive damages have, however, increased considerably due to the higher service life on the one hand, and due to the improvement of materials as well as the provision of designs with optimum weight characteristics on the other hand.

If, for instance, the requirement for a high service life is taken as an example, it must be ensured that:

1. All materials susceptible to corrosion are given a double surface protection.

2. Areas which are inaccessible or difficult to reach or inspect, and areas which are subjected to considerable condensate moisture must be given an increased corrosion protection.

3. All steel fasteners with sealant must be installed wet.

4. Depending on the state of installation, assembled components must be preserved with sealing compound and a paint coat to avoid any penetration of moisture, especially at the fits.

Furthermore, the behaviour of protective coatings after forced injuries must be known in order to be able to draw conclusions about the greater or lesser loss of the protection under practical load conditions.

2.1 Chemical treatment processes (Fig. 1)

This chapter is to give a brief description of cleaning procedures and special pickling processes as well as systems with which the cover layer is formed by chemical reactions without applying current, Fig. 1.

Chemical surface treatment generally requires the following treatment stages:

- 1. Degreasing and cleaning
- 2. Pickling
- 3. Formation of cover layers, e.g. chromating, phosphatizing.

2.2 Alkaline pickling processes

Pickling processes primarily serve to remove mill scale. Within the scope of chemical and electrochemical surface treatment procedures with layer formation, it is imperative that the natural oxide layer be removed in order to achieve perfect and uniform coatings.

Pickling processes are broken down into alkaline and acidic processes.

The advantage of alkaline processes as compared to acidic processes is that they attack the various aluminium materials more strongly and can be used in baths made of unprotected normal structural steels. Caustic soda is the basis for alkaline pickling processing.

When alloyed aluminium is treated in alkaline pickling solutions, the constituents of the alloy become apparent. Especially copper and siliceous alloys but also aluminium materials containing magnesium and manganese reveal strong discolourations after pickling. Consequently, it is necessary to remove the coatings occurring during pickling. This is achieved with neutralizing agents.

2.3 Alu-chromating (Fig. 2)

The tendency of a material surface to obtain by reaction with the surrounding materials a cover layer that is more resistant than the base material has prompted engineers to initiate such reaction processes "artificially".

Alu-chromating has come to be particularly important as a pre-treatment provided prior to applying the surface treatment layers. Although the chromated layers serve as a surface protection in this case, they also assume an important role as a wash primer between the metal surface and applied films of varnish.

Alu-chromating is understood to mean the treatment of aluminium alloys with an acidic aqueous solution containing hexavalent chrome, thus forming a protective layer consisting primarily of aluminium-chrome compounds on the surface of the metal.

The reaction taking place during Alu-chromating can be shown schematically as in Fig. 2.

2.4 Anodic treatment process (Fig. 3)

All anodic treatment processes are based on the artificial formation of an oxide layer on the surface of the metal. It is thus possible to obtain thicker and better protective layers than in the case of oxide layers formed in the air. The processes for artificial generation of oxide layers can be carried out with positive overvoltage (Fig. 3).

Under the influence of an electric current (Fig. 4) atomic oxygen develops at the anode during the electrolysis. The oxygen reacts with the aluminium, thereby forming aluminium oxide which is linked to and remains adhered to the metal surface thus forming the anodic oxide layer. The anodic oxide layer propagates into the metal by the directest way.

Direct current sulphuric acid anodizing for light metal may only be used in areas with considerable abrasion and not for parts that are subjected to dynamic loads, since the fatigue strength of the material is reduced by this process.

2.5 Cathodic treatment processes (Fig. 5)

Electro-deposited protective layers belong to the main group of cathodic treatment processes with negative overvoltage. Although originally only used as decorative coatings, electro-deposited coatings have long since acquired technical significance and, in their many variants, are used not only for corrosion protection but also to retard wear.

The electro-deposited layers are produced for various purposes. They often serve to give other layers or combinations of layers an improved resistance to tarnishing and a high resistance of the protective layer to certain media. Electrolytically deposited layer tends to be brittle, a fact which has to be taken into consideration especially where thicker layers are concerned. Moreover, allowance must also be made for the fact that metal layer plated parts are subjected to stress and deformation when used.

Furthermore, the possibility of fatigue loads must already be taken into consideration when the metal layer is deposited.

2.6 Organic coatings

The group of organic surface protection materials is headed by varnishes. Varnishes are materials that are applied in form of a liquid and, through chemical or physical changes, form a thin layer - also called film - adhering more or less strongly to the covered areas. Ideally, varnished items are thus covered by an uninterrupted layer which prevents or at least retards the attack of aggressive materials on the protected surface.

The protective effect of varnishes is, however, limited to a certain extent on account of the fact that, due to diffusion, osmosis and capillary action, a certain exchange of material can take place between the stressed medium and the coated surface.

In aircraft construction, surface protection systems made up of several and often many layers of different materials have proved successful. A system frequently applied consists of a two layer varnish with pre-treatment. The tasks of the individual layers are such that the wash primer protects the cleaned surface until the varnish is applied and keeps it passive.

The priming paint is strongly pigmented so that it offers a covering and filling base for the final coat. The top coat has a higher binder content, and can thus form a non-porous and elastic film which is largely resistant to the attacking media and considerably retards any penetration of aggressive or physically active substances to the depths of the coating and even to the metal surface.

3. DESCRIPTION OF CORROSION CASES

It is difficult to find a systematic approach and breakdown on account of the many cases of corrosion and corrosion phenomena.

3.1 Electrochemical processes at electrodes (Fig. 6)

Initially, it will be useful to recall some of the theories of electrochemistry in order to deduce the bases of corrosive processes. The schematic diagram given in Fig. 6 will help to illustrate this.

The metal changes from the atomic to the ionic state as a result of the electrolytic solution pressure of the electrode. This corresponds to the anodic electrode reaction (oxidation).

The case shown in Fig. 6 is as follows: three electrons remain in the metal specimen when three metal atoms leave the metallic structure and dissolve as Me^{+}-ion.

The tendency of a metal to discharge its electrons can be deemed as a measure for its effort to dissolve.

This tendency can be determined by electrical measurements and expressed as the "electrode potential" of the corroding system.

A reference electrode is here used in a defined and constant potential, e.g. a calomel reference electrode, Fig. 7.

4. EXAMPLES OF THE CORROSIVE BEHAVIOUR OF ALUMINIUM ALLOYS

4.1 Pitting corrosion (Fig. 8)

Strictly speaking, pitting is only seen to occur on materials capable of being passivated and consists of local corrosion in a surface which, for the rest, is passive. Pitting corrosion only occurs when halogen ions exist in the attacking electrolyte.

The halogen ions cause the passive film to collapse at weakened points, hence making these points active. Weak points are brought about by any particles being deposited on the surface, making the supply of oxygen difficult and preventing a complete passivation.

If the passive film on the metal surface has been destroyed at many locally limited points, a strong dissolution of the metal will commence at the points which are now active and a rapid propagation in depth is seen to occur.

4.2 Intercrystalline corrosion (Fig. 9)

The prerequisite for an intercrystalline corrosion attack, which forms cracks penetrating deep along the grain boundary, is that there are deposits at the grain boundary.

Aluminium alloys in an oversaturated state are not under all circumstances susceptible to intercrystalline corrosion; on the contrary, certain conditions must be fulfilled in respect of the chemical composition, the thermal treatment and the degree of cold-forming of the workpiece, and in respect of the corroded medium. Intercrystalline corrosion occurs when the deposits are finely dispersed and in coherent form.

4.3 Layer corrosion (Fig. 10/11)

Layer corrosion mostly only occurs on some high-strength aluminium alloys in sheet form in the presence of certain structures and under the influence of certain corrosive media. This type of corrosion is characterized by the fact that preference is given to a selective corrosion, propagating in parallel to the direction of forming and possibly causing the surface to flake off. "Genuine layer corrosion" of aluminium exists when the attack is transcrystalline.

4.4 Stress crack corrosion (Fig. 12)

A further type of corrosion, namely stress crack corrosion, manifests itself when a material having no deformation suddenly ruptures when electrochemical reactions and mechanical stresses are superimposed in the presence of a suitable chemical agent. In the case of stress crack corrosion, widely branched intercrystalline cracks suddenly develop which can result in an immediate rupture.

It appears that the formation of passivation layers is a prerequisite for stress crack corrosion, as no system of metal and attacking agent in which a damage occurs without cover layers being formed is known.

In the case of aluminium, this applies to aluminium oxides and hydrates; in this case, anodized coating according to the chromic acid procedure is concerned.

4.5 Contact corrosion (Fig. 13)

In the case of contact corrosion, at least two phases with different potential are in direct contact and linked by an aqueous solution. Consequently, a closed circuit exists. Depending on the potential, the two phases act as the anode and cathode of a galvanic element. Metallic platings, as frequently used for corrosion protection, belong to this category, Fig. 13.

Pure aluminium plating protects the inner alloy cathodically, since the outer plating acts as sacrificial anode much like a zinc layer on steel.

Components which are joined by means of fasteners (Fig. 14) are highly susceptible to corrosion in the area of the joint if materials having a different resting potential are joined such as to be electrically conductive. Procedures have been developed for titanium threaded fasteners, enabling a rational coating of the lower surface of the head with a sealant.

The sealant serves to fill the countersinks during installation such as to prevent any penetration of the electrolyte to the greatest possible extent. The corrosive behaviour of the metal combination "clad aluminium alloy/titanium alloy" has been investigated.

The transitions between "external surface/countersink" partly revealed minor corrosion. The microscopic examination showed that primarily the cladding had been attacked.

4.6 Filiform corrosion (Fig. 15)

Damage to the paint coat at components, countersinks, holes and edges has occurred during assembly work. In contrast, the minor relative motions occurring in flight are to be held responsible for the formation of hair cracks in the paint coats. Salt nuclei primarily consisting of sodium and calcium salts exist at these centers from which the cracks start out.

Owing to their great affinity to water, these initially dry and water-soluble salts absorb water vapour from the moist atmosphere through their coating until an aqueous solution is formed. Osmotic processes are responsible for this. Anodic and cathodic part reactions take place on account of the electrolytes that have developed.

The anodic reaction leads to a very minor depth attack of the plating. The electrodes of the anode are consumed during the cathodic process and 6 OH-groups are formed. These, in turn, precipitate the dissolved aluminium as aluminium hydroxide. The head and body of the thread develop, these being separated from the center from where the crack starts out. The precipitated corrosion products form a diaphragm between head and body. The salt solution originating from said center is present in the head and is pushed further by the body without notable losses in concentration. Water losses in the head are compensated by osmosis; in contrast, the aluminium hydroxide is dehydrated causing the corrosion products to crack open.

5. NON-DESTRUCTIVE TEST METHODS TO DETERMINE CORROSION

The equipment used for the novel test methods mainly consists of:

- electrochemical detector
- required voltage transducer
- electronic control unit
- ampermeter
- voltmeter
- x-y plotter
- reference electrode

Diluted phosphoric acid is used as electrolyte.

Aluminium alloy 3.1364.5 was examined

- in its delivered condition
- in a corroded condition

5.1 Examination of the material 3.1364.5 (Fig. 16/17)

Fig. 16 shows the current density-potential curve of material 3.1364.5 in its delivered condition.

Fig. 17 shows the development of the current density-potential curves for material 3.1364.5 after 41 hours of subjection to a corrosive medium.

The passivity and natural oxide layer of the surface have been cancelled due to the 41-hour effect of the corrosive medium, so that the breakdown potential without a passive area changes from the cathodic to the anodic range (Fig. 17). The irregular course of the curves is to be attributed to secondary reactions in the micro-range-penetration of the electrolyte into capillaries and corrosion products.

Corrosion attack is confirmed by way of a metallographic investigation.

The drop in current density at 2000 mV from 0.65 mA/cm^2 (1st curve) to approx. 0.3 mA/cm^2 (5th curve) shows that the phosphoric acid which has been used as electrolyte has a good passivation capability. A clear passivation only occurs after approx. 25 cycles.

These results show that it is possible to apply electrochemical procedures for non-destructive testing to determine corrosive damages within the scope of aircraft maintenance.

23.2.1981

Dr. La/be

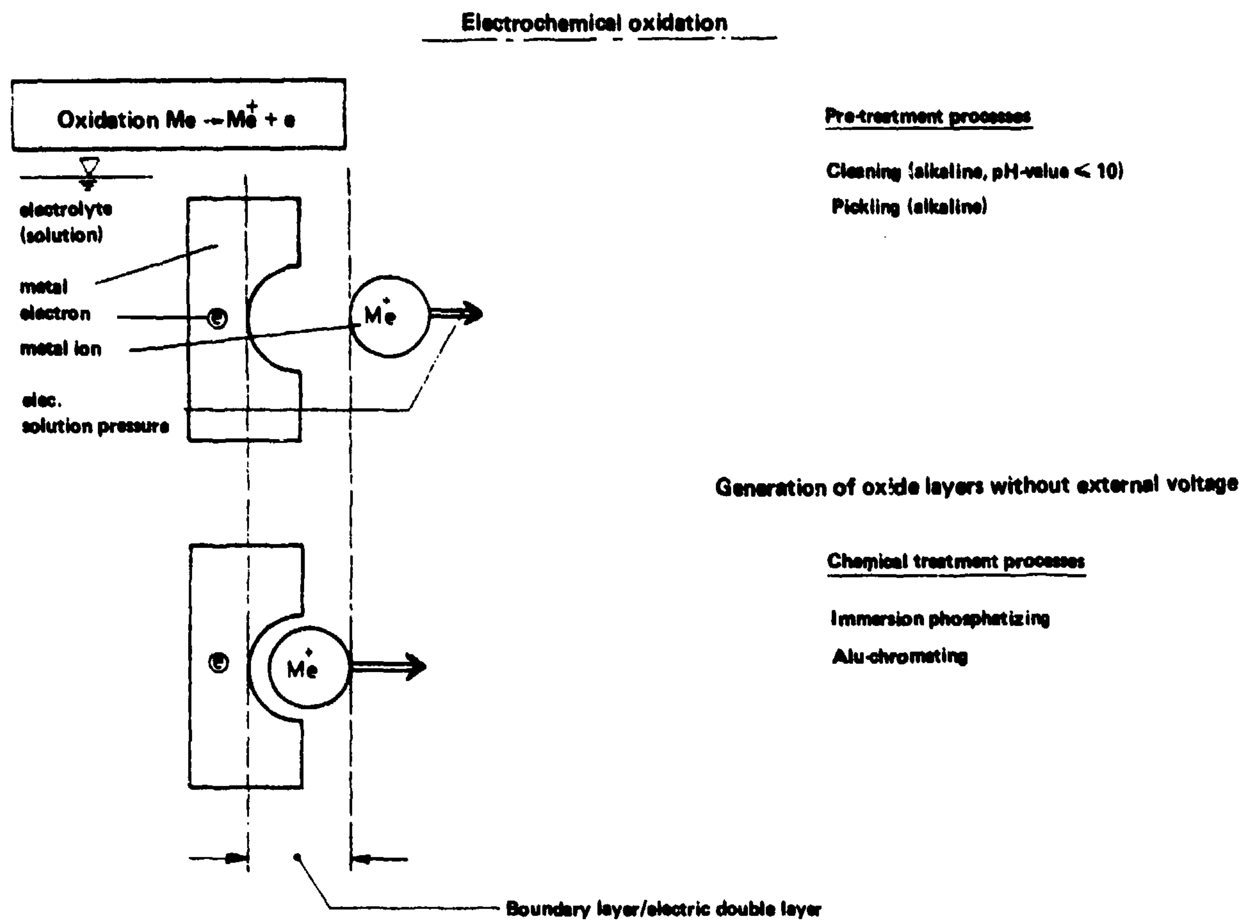


Fig.1 Chemical treatment processes

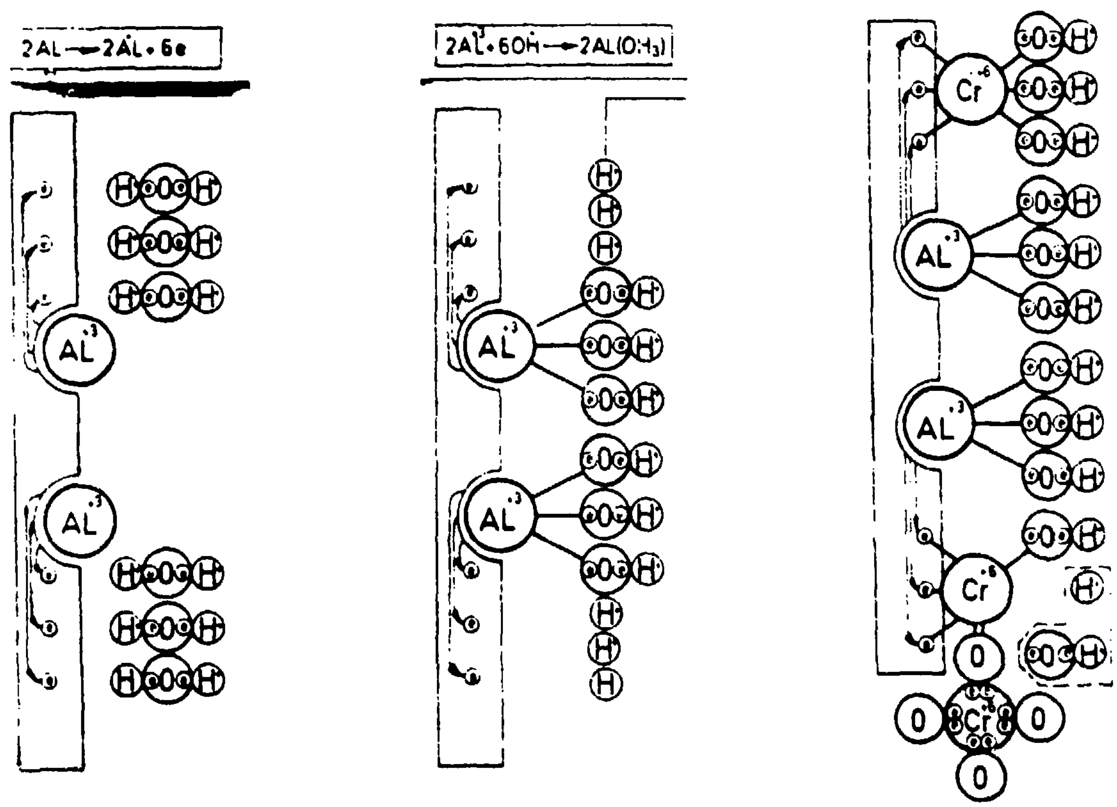


Fig.2 Chemical reactions during Alu-chromating of aluminium

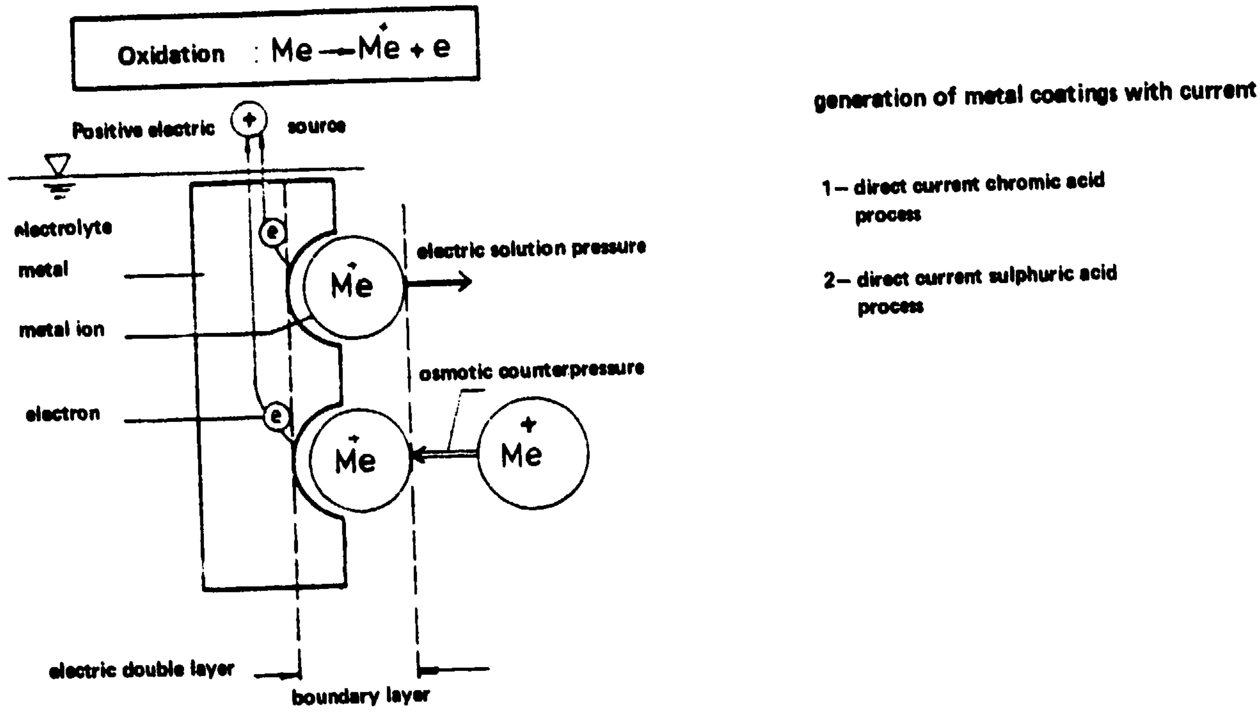


Fig.3 Anodic treatment procedures

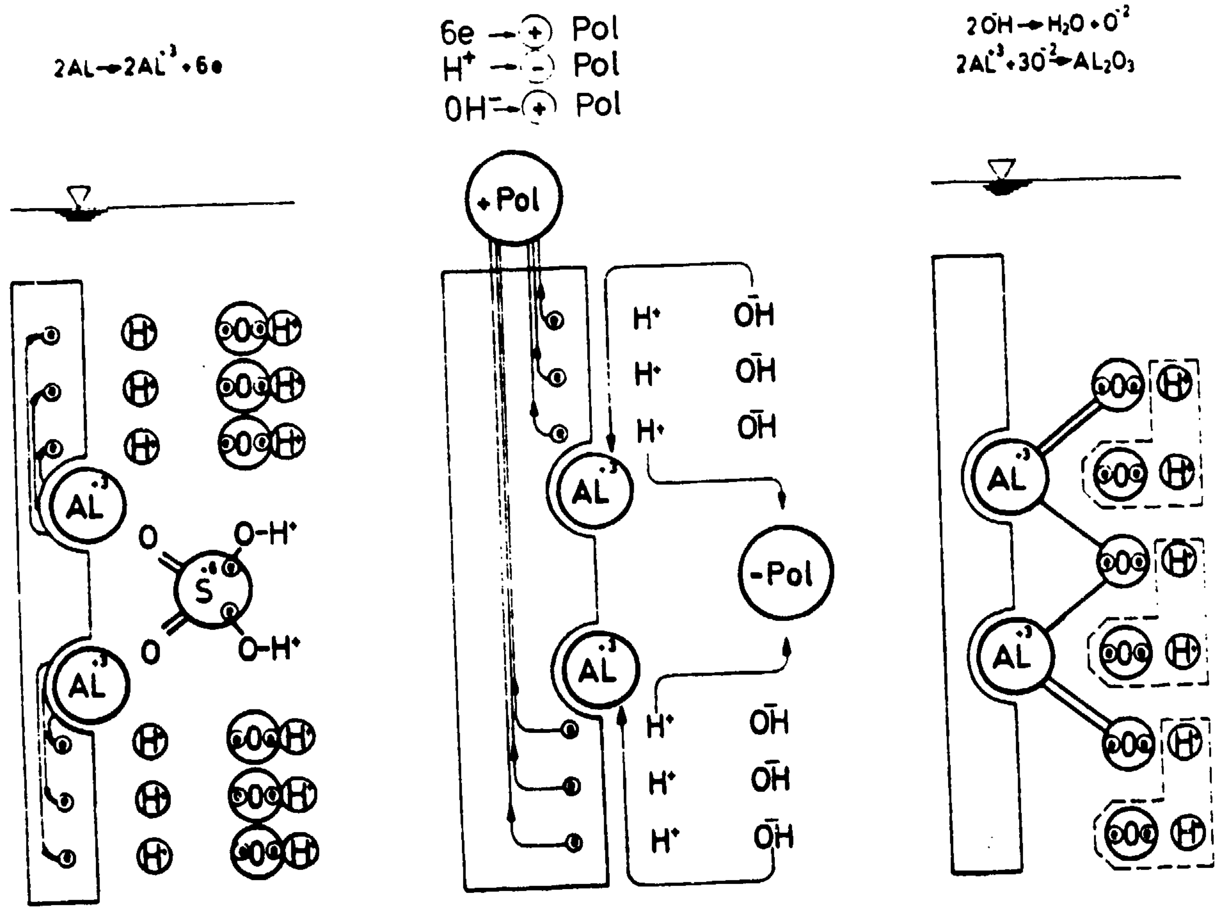
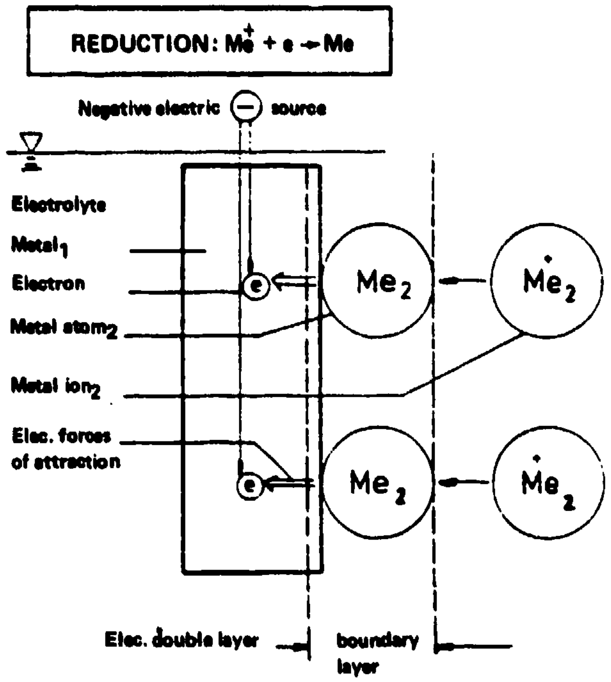


Fig.4 Direct current anodizing process



GENERATION OF METALLIC COATINGS WITH CURRENT

1 – Cadmium-plating
2 – Galvanizing
3 – Hard-chromium plating
4 – Copper-plating
5 – Nickel-plating (electrolytic)

Fig.5 Cathodic treatment process

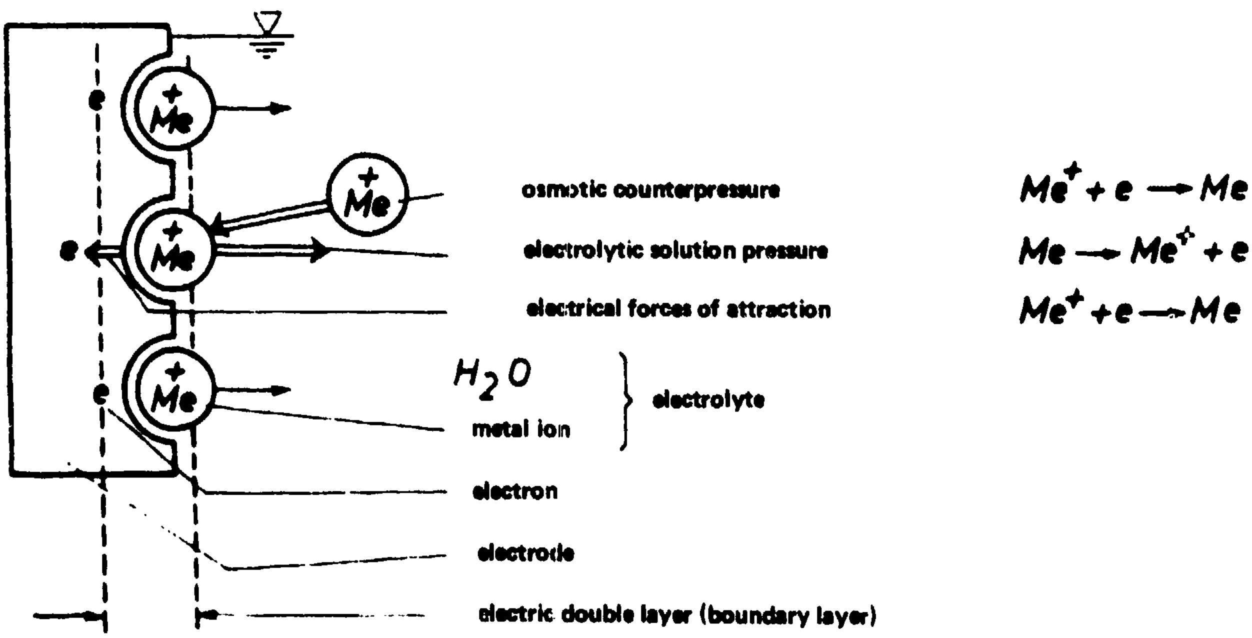


Fig.6 Forces at metal ions

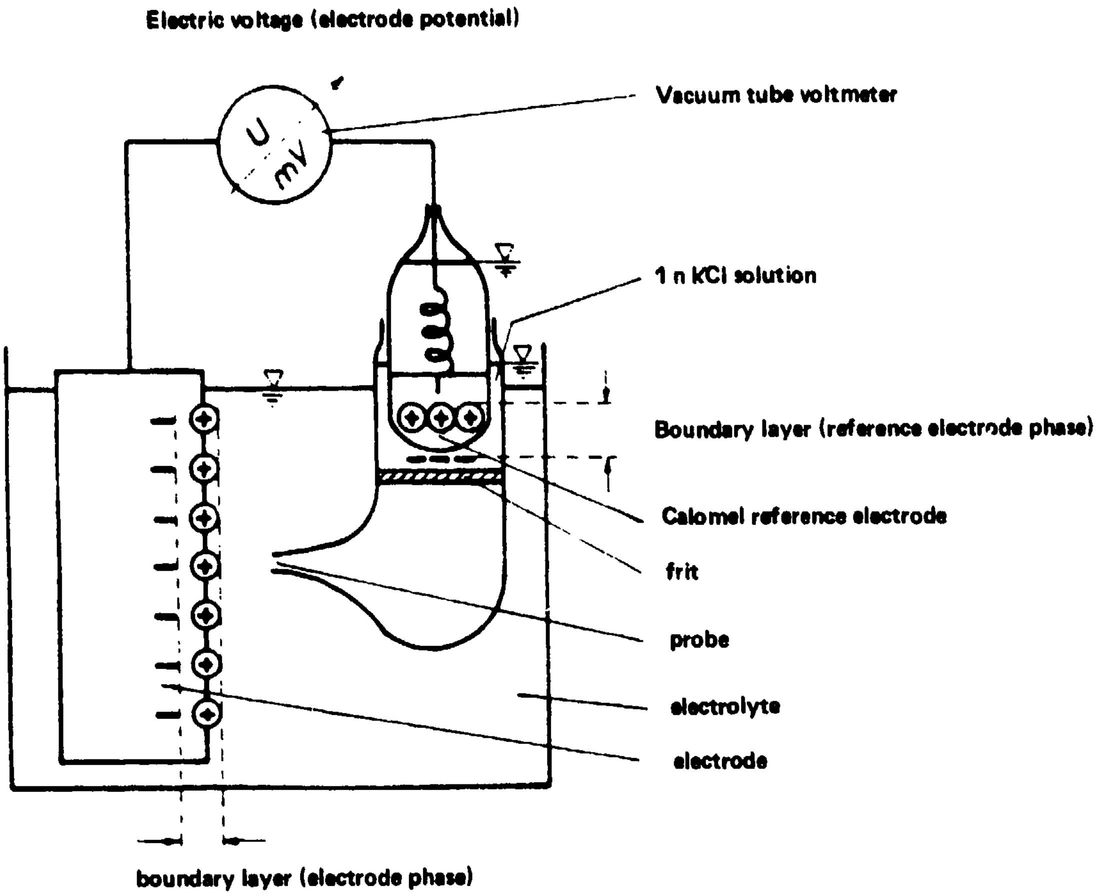


Fig.7 Determination of electrode potential

Fig.8 Pitting corrosion

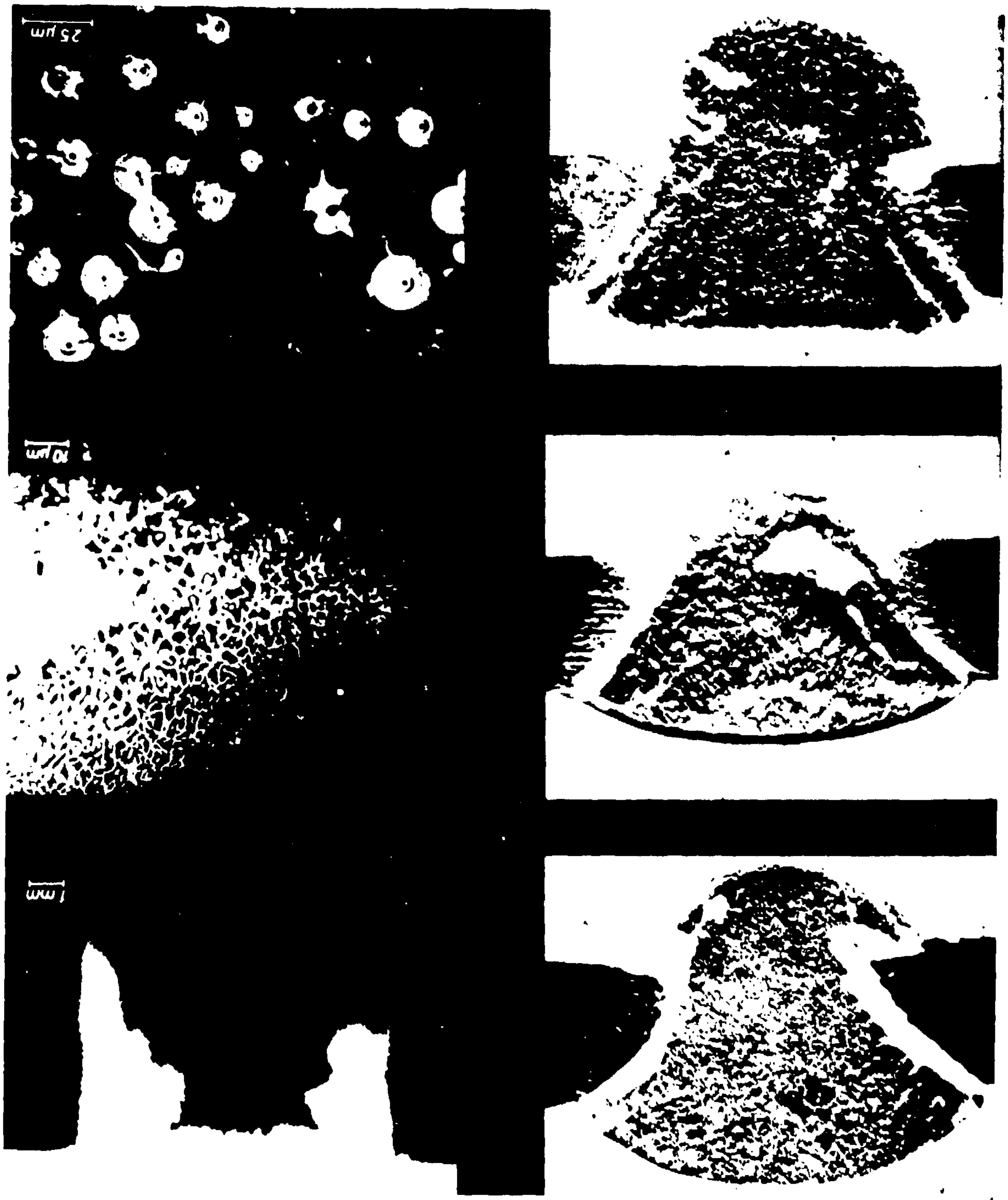
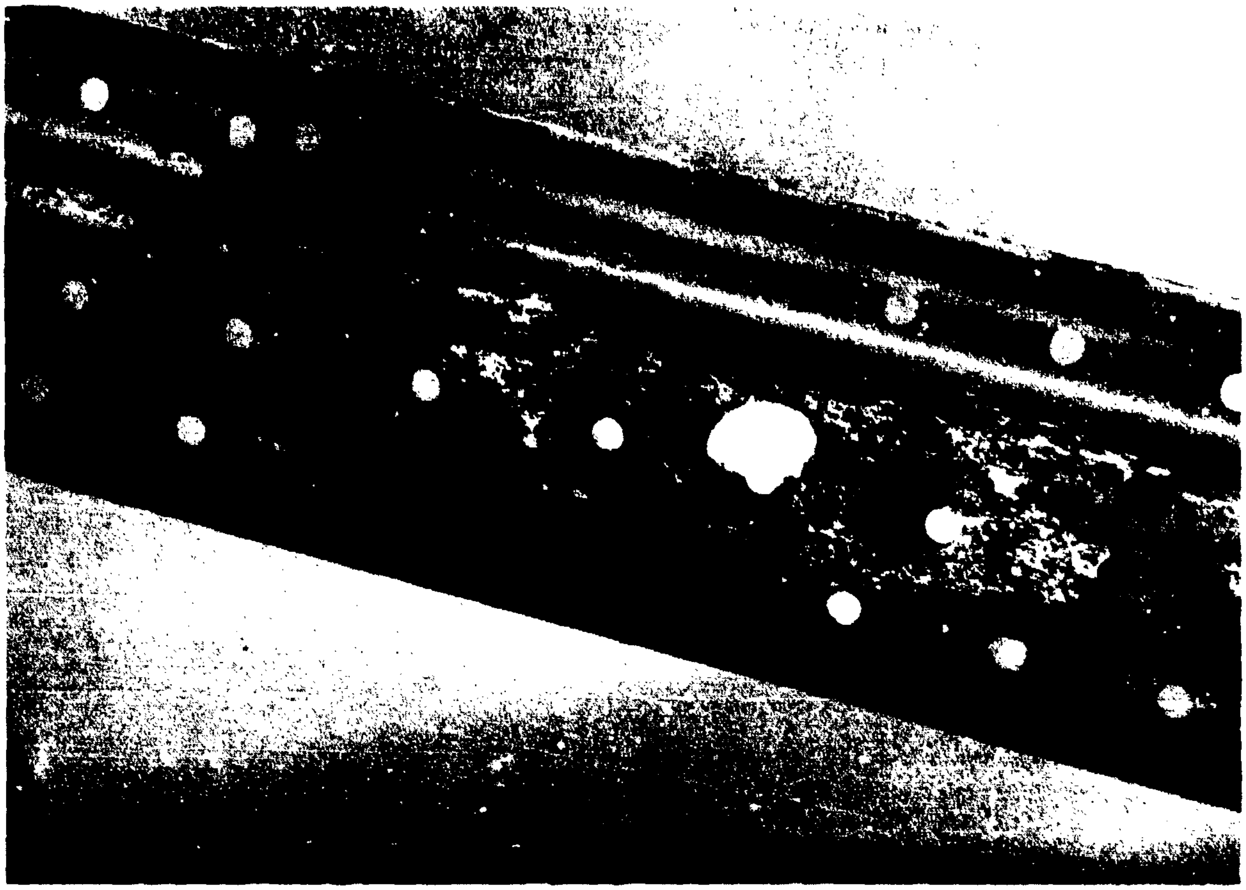


Fig.9 Intercrystalline corrosion



Material: 3.4364 (Cu 1,74 %, Zn 5,38 %)

Fig.10 Corroded stringer

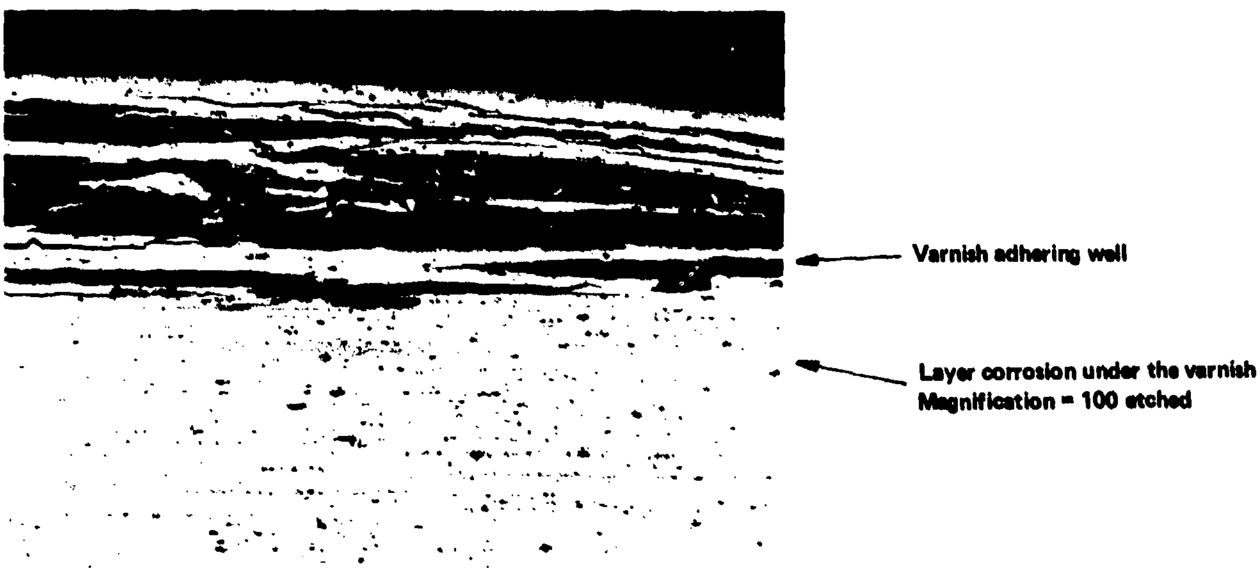
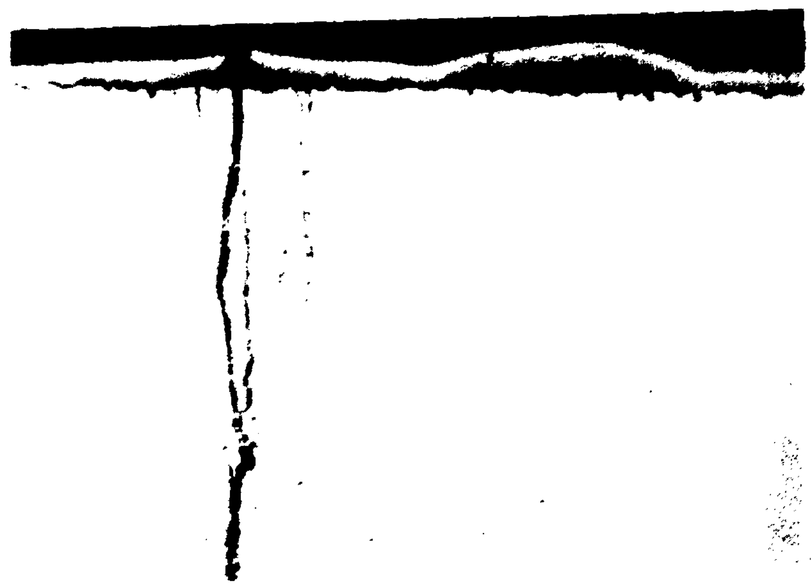
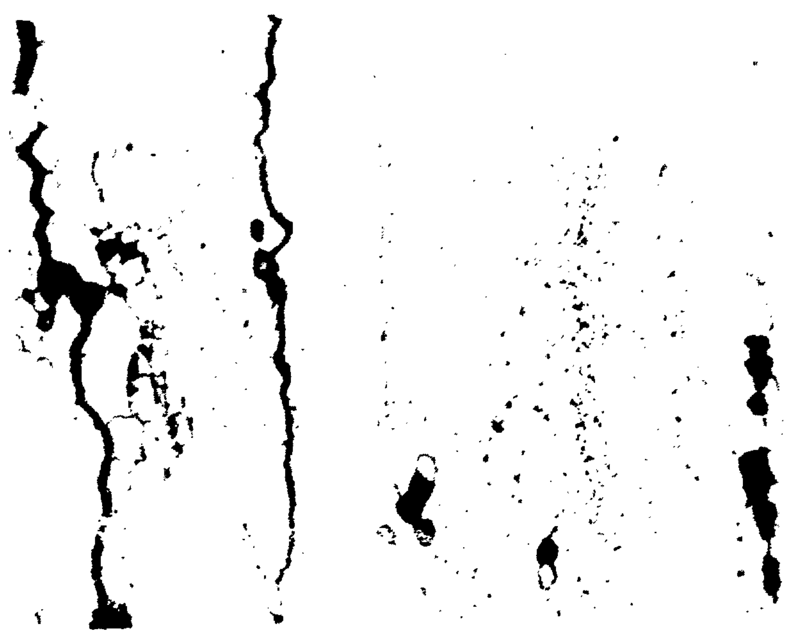


Fig.11 Layer corrosion



b) Macroscopic crack course 75 fold magnification



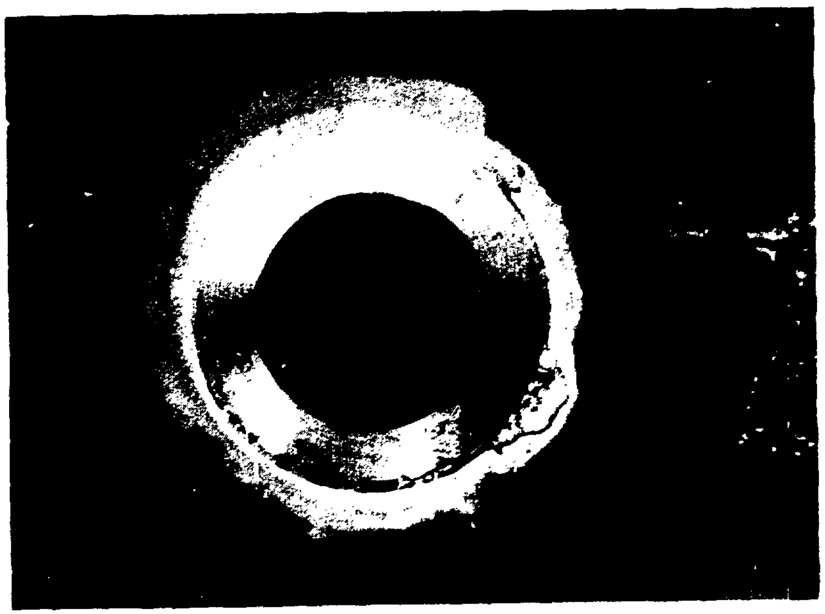
c) Crack course in micro-structure 1000 fold magnification

Fig.12 Stress crack corrosion

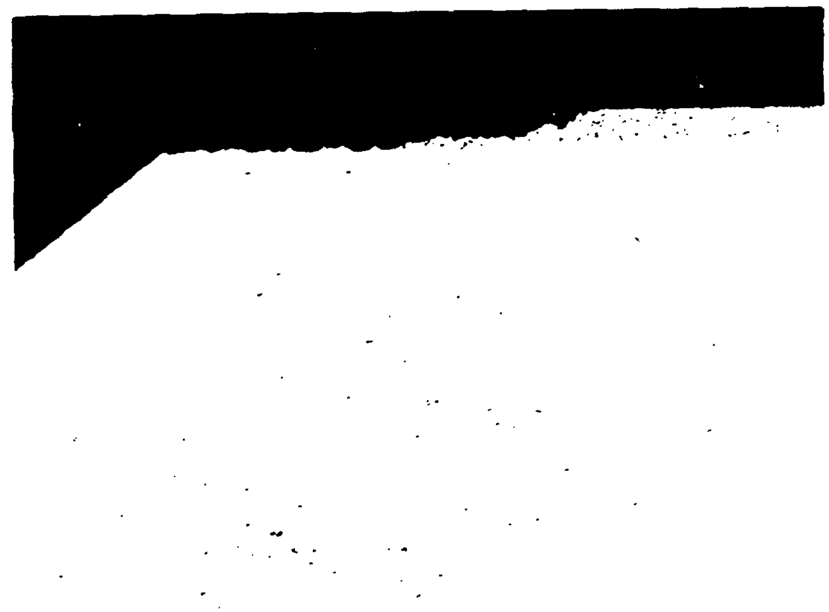
plated, *magnification* 1000 : 1

unplated, magnification 100 : 1

Fig.13 Corrosive behaviour of plated and *unplated aluminium* alloys
Contact *corrosion*



magnification 5 : 1



magnification 50 : 1

Fig. 14 Contact corrosion of the counter sink

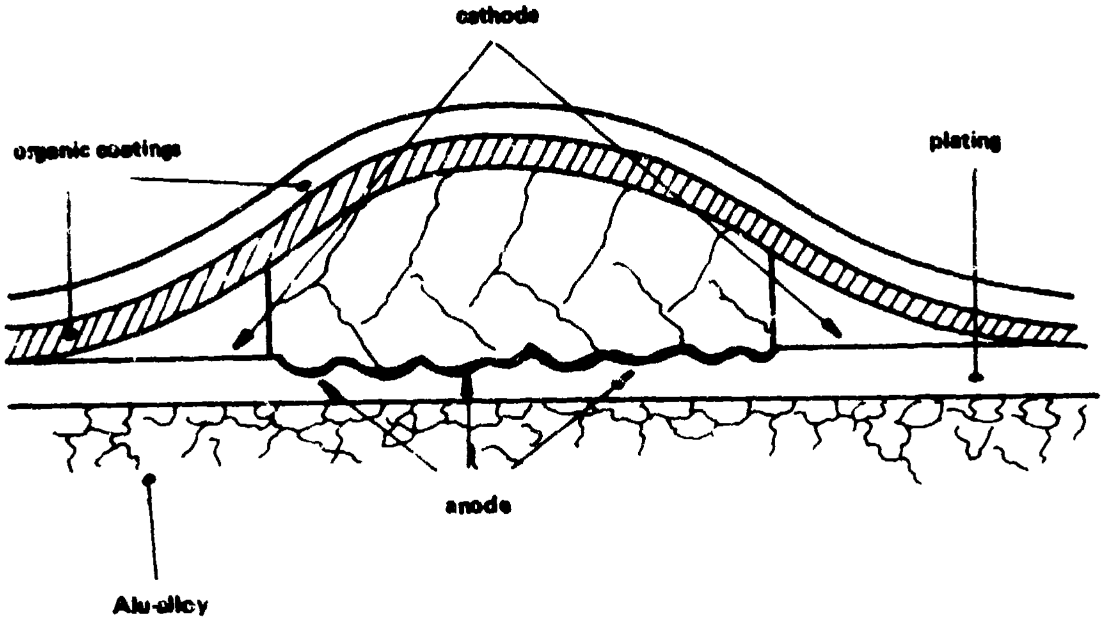


Fig.15 Schematic arrangement of the Filiform-corrosion

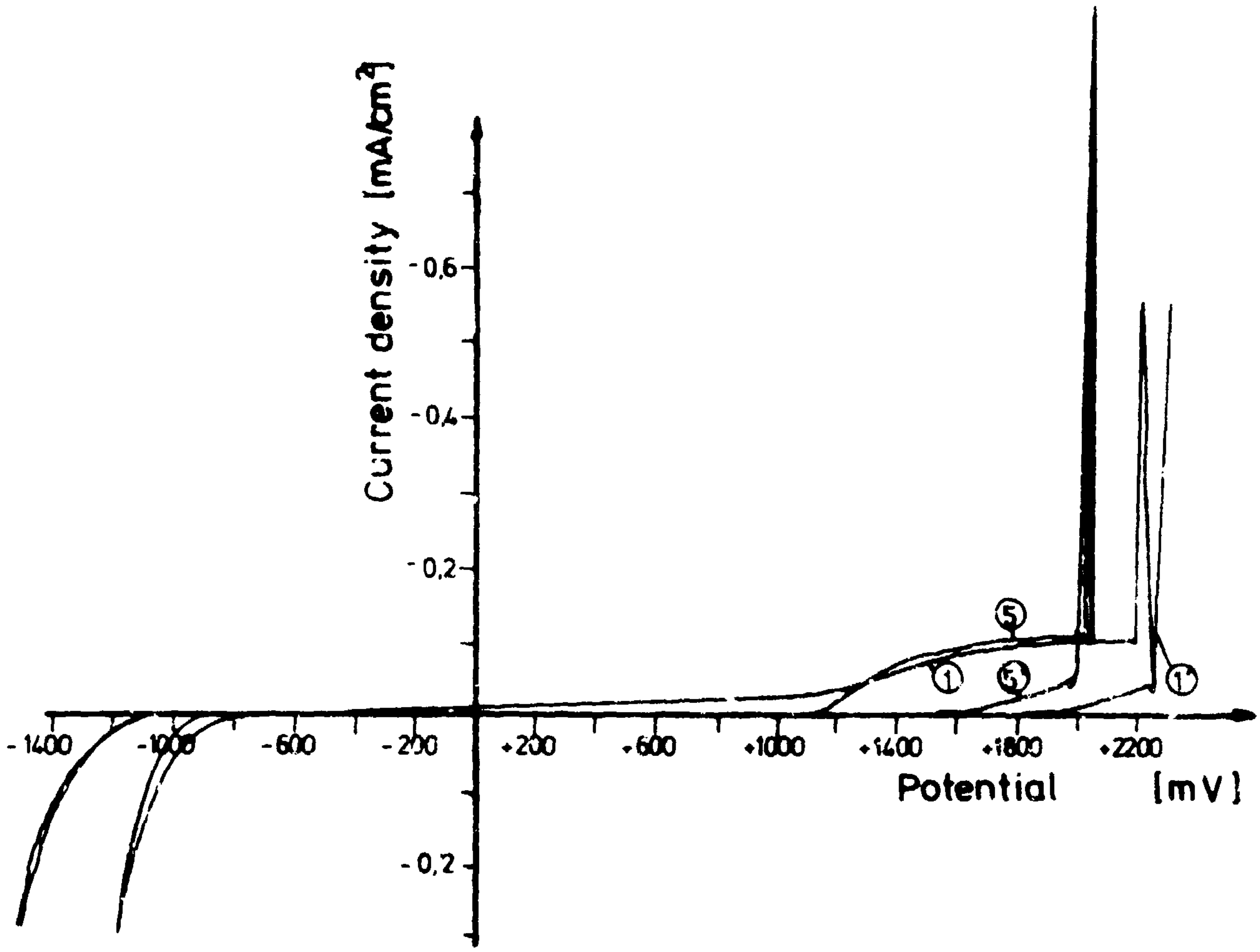


Fig.16 Current density-potential curve of Alu-alloy

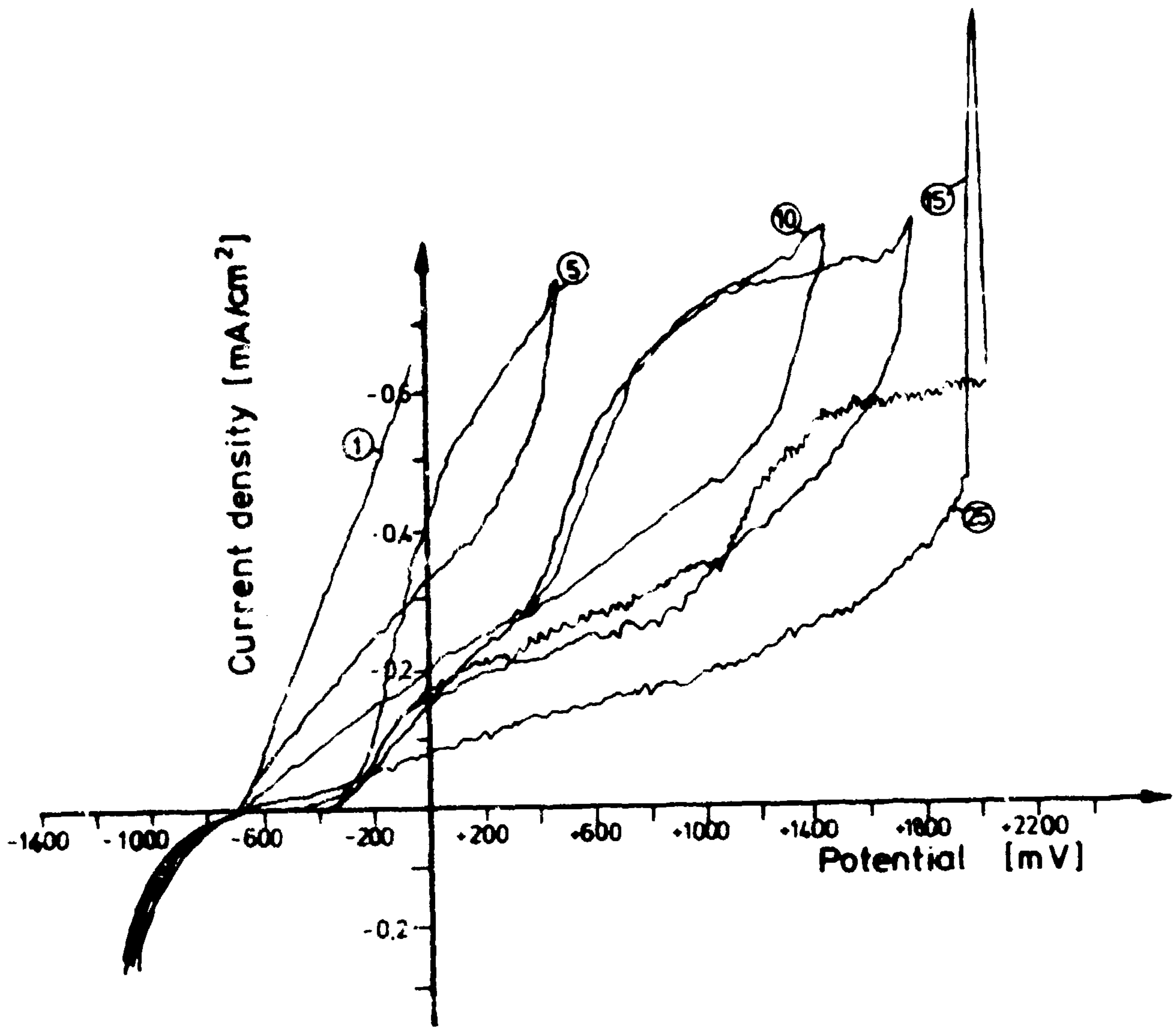


Fig.17 Current density-potential-curve of Alu-alloy

RECORDER'S REPORT – SESSION III

by

Dr John J. De Luccia
Head, Materials Protection Branch
Naval Air Development Center
Warminster, PA 18974

This session was titled, "R&D in Best Anti-corrosion Practices". It consisted of four papers, the first of which I delivered, which was titled, "Recent Developments in Materials and Processes for Aircraft Corrosion Control". In that paper I attempted to describe the current state-of-the-art corrosion control practices, and then I also tried to look at the future and describe some on-going research that will provide us with new corrosion control products, procedures and techniques.

The second paper was titled, "New Concepts in Multifunctional Corrosion Inhibition for Aircraft and Other Systems", by Dr M.Khobaib of Systems Research Laboratories under contract to the United States Air Force. Here Dr Khobaib describes some new inhibitors that he was solubilizing in the aqueous phase that would be utilized in the rinse water and wash water that airplanes could be subjected to, and he describes some rather basic and fundamental corrosion studies in that he plotted the potential versus the log of the current of various inhibitors in sea water on substrates as aluminium and steel, and with this he defined passivity and passive regions. He observed that with the incorporation of certain inhibitors the passive regions were enlarged and the corrosion current was reduced. Hopefully, when these inhibitors are incorporated in wash water, beneficial effects will be noted.

The third paper was titled, "Corrosion in Naval Aircraft Electronic Systems". This was delivered by Mr Irving Shaffer of the Naval Air Development Center, United States. Here Mr Shaffer talked about a subject that has been sorely neglected in aerospace. We've been concerned with airframe corrosion; we have been concerned with propulsion corrosion; but we have neglected electronics corrosion, and it turns out that it is something that we neglect at our own peril because it is an extremely important subject. Mr Shaffer indicated and showed how, under certain circumstances, the aircraft aboard United States aircraft carriers sometimes have their access doors and canopies opened and this then allows sea spray to come in or rain to enter, and this is all done inadvertently people maintaining the electronics in other ways but corrosion is occurring. Mr Shaffer also indicated that the manufacturers of electronic equipment are not truly concerned with the corrosion control procedures and requirements of their products they're concerned with the performance, they're concerned with whether the black box will work. And up to very recently, even the users the United States Navy were not aware that we had such a severe problem. In the recent past Mr Shaffer has indicated that the United States Navy, under his active participation, has issued a manual, NAVAIR 540, a corrosion control manual, for avionics equipment which is proving to be very beneficial. Mr Shaffer also brought up, later on in the question period, the possibility of looking at a new departure in connectors. We find that the connectors of electronic equipment pose a particular corrosion problem. It would be desirable to make these connectors out of something that would not corrode. This could be a composite plastic material that would also be conductive because of the EMI requirements. Mr Shaffer described these requirements.

The fourth paper, was titled, "Corrosion Protection Schemes for Aircraft Structures", and, specifically, aluminium alloys. This paper was delivered by Dr Lajaine of VFW-Fokker, Germany. It was very interesting to see that Dr Lejaine introduced and talked about concepts that are very, very basic to the event of corrosion. I think it was very necessary for us to see the fact that at the surface of an actively corroding metal there is a double layer. It was very necessary for us to see that the metal goes from the atomic state to the ionic state. I think it was also necessary for us to see that there are such things as reference electrodes and that the concept of electrochemistry is truly or the concept of corrosion is truly interdisciplinary in that you have a surface, and at that surface corrosion occurs, but on one side of the surface you have the metal and this is where the metallurgists are active. On the other side, you have the environment, which is where the chemists are active. So I think that Dr Lejaine's paper pointed out that the chemists have to start talking to the metallurgists, because the event that's going on doesn't know the difference between the two disciplines. He had some very good slides, and he stimulated some discussion on the aspects of pitting and intergranular corrosion.

Right now I'd like to comment on some of the questions that each of the speakers had and then we will be open to the general discussion. In my paper I had a number of questions. One concerned itself with the use of powder metal alloys as new alloys for corrosion protection, and the question was raised of porosity and fatigue properties. Much discussion ensued concerning these advanced topics of processing such as hot isostatic processing, 100% density attainment, the working of the alloys after "hipping" to near net shape. The question, also, was raised about the compatibility of certain elastic or elastomeric compounds in coating systems with regard to whether a layer of polyurethane will adhere sufficiently to a layer of polysulfide, and some of these newer concepts of flexible paints were discussed. When I talked about the molten salt process of depositing aluminum onto steel, the question was asked at what temperature is this done and if you were to deposit aluminum onto aluminum would you destroy the heat treatment, and we talked about the fact that the process doesn't take very long and the temperature of operation is in the area of 350°F (in "real units" I think that's 160°C). Another question was how long will AMLGUARD last. And the answer to that was it depends on the application. If you're not in the erroding condition, the AMLGUARD can last months, even years.

Going to the second paper, there were no questions. However, I have an observation with regard to the second paper. It was noted that Dr Khobaib presented data that was not included in the published preprint. I bring this out for your information at this time. The published preprint did not contain corrosion fatigue data that Dr Khobaib presented yesterday.

In paper three, Mr Shaffer was asked whether we are looking at the cadmium plating on aluminum as opposed to nickel plating on aluminum for electrical connectors because of the problems that the nickel can give with regard to pitting corrosion. Mr Shaffer indicated, yes, we are looking at cadmium-nickel combinations on the surface of the aluminum connectors. And, of course, Mr Shaffer also brought out that we are looking for a better solution, conductive polymers. These would be used instead of having a metallic connector. He talked about a 40 weight percent graphite polyphenylsulfide which appears to have great promise as a conductive polymer for connectors that would not corrode.

In the fourth paper I brought up a question to Dr Lejaine concerning the cladding on a photomicrograph that was shown on the screen, and it was answered that the photomicrograph was 2024 aluminum and the cladding was 1100 aluminum alloy. Now 1100 alloy is supposed to be sacrificial to the underlying 2024, however, the photomicrograph gave the appearance that it was not sacrificial. Mr Staley from the Aluminum Company of America, made the observation that this was perhaps a singular event and is not typical of 2024 cladding.

RECORDER'S REPORT – SESSION IV

by

Prof. R.J.H.Wanhill
National Aerospace Laboratory (NLR)
P.O.Box 153
8300 AD Emmeloord, The Netherlands

ROUND TABLE DISCUSSION

In the following a nominally verbatim transcript of the discussion has been prepared from tapes. Minor alterations have been made by discussers in the interest of clarity. The transcript is followed by a short summary of the various recommendations that were made. This summary has been prepared by Dr. W. Wallace, the meeting chairman.

G.T. Browne (Cdr Naval Air Force Atlantic Fleet), Session Chairman

Well, ladies and gentlemen, I guess the floor is now open for discussion. I would like to add one item. I feel that the discussions on design, training, should produce some recommendations from this group to the AGARD Structures and Materials Panel for an attempt to get some kind of action in our countries to change these things. That's all I have got to say. The floor is now open.

T.F. Kearns (Institute for Defence Analyses)

Mr. Chairman, I'd like to make just a few comments at this point, because I think we have an opportunity at this meeting to do something that we very seldom have an opportunity to do. Usually, the Research and Development community meets and talks about corrosion. The field operators, the users, meet and they talk about corrosion. The two don't usually get together, but at this meeting we have operators, constructors and the R and D community and the purchasers of aircraft. I think it would be well if we could exploit this fact and get a cross-dialogue.

I don't think, for example, that it is the best use of our time today to have an argument about technical things in R and D between R and D people. We have plenty of opportunity to do that, but we don't have much opportunity to have the users and the R and D community talk to each other. I think we would be well advised to exploit this advantage today.

The kind of question, for example, that we might address ourselves to is an answer to how we can convince - and whom we should convince - people to apply better corrosion practice. Everybody says "They don't do it. We know how, but they don't do it". We all agree that it is cheaper to prevent corrosion than it is to fix it. Prove it! If we could in fact prove it effectively and persuade the people who write the specifications to require best practice, then we would have achieved the objective we seek. We can't convince a manufacturer to do anything except to meet the requirements of his specifications at the lowest possible cost. That's his job: his job is not to build the most corrosion resistant airframe. If he had used titanium rivets instead of steel rivets and bolts, they wouldn't corrode but they'd be much more expensive.

So I think its these things that we might well address ourselves to today. If there are procedures which will bring the experience of the user more forcefully to bear on the people who write specifications, and we can identify such procedures, I think that would be a very desirable and effective outcome from this meeting. Thank you.

G.T. Browne

I agree with what you said there, and I think if we accomplish that, the meeting will be really worthwhile because that's where the root of our problem has been identified to be, is getting to the people who are writing the specifications and the standards for the design and procurement of aircraft.

The floor is open. Any comments?

D.M.F. Bright (Ministry of Defence, Air Eng. 30)

May I say first of all how heartily I agree with Tom's previous statement. Operators are always trying to get their message across to the source from where we get our next generation of airframes, and this applies whether we're talking military or civil, of course. Having said that, we do appreciate there are a lot of difficulties in the way of implementing what we'd like to see implemented.

I would like to take up two points very briefly. One was the query of the statement made by us that we hadn't lost any aircraft due to corrosion. The query did made us really appreciate that certain failures might be in fact initiated at the fundamental level by corrosion phenomena I think in answer to that I would say that if we have any major structural failures we will chase the causes down to the fundamental level, as far as we are able, by consultation with the Royal Aircraft Establishment, the Design Authority, and so on. Relatively trivial failures - individual electronics failures, perhaps, which don't hazard the aircraft - don't get the same degree of attention. We have had some near escapes: we had a heavy jet aircraft at the end of last year which had a major landing gear failure which was caused fundamentally by galvanic action which initiated stress corrosion cracking. But, as I say, we haven't had, to my knowledge, any complete failures of structural integrity in the air.

We have - incidentally I would mention - we have talked about costs, but of course we are also concerned with structural integrity as the final responsibility. May I just say a second word on this question of the design process. We must try and make sure that our regulations and design specifications do give the design authority guidance. But I would say, as did Mr. Versteeg, who talked about signing - off drawings for corrosion, I've heard people talking about signing - off drawing for fatigue, I've heard people talk about signing - off drawings for reliability and maintainability. And this to me indicates that there are a lot of very complex factors which have to be taken account of in design, and this must be I suppose a question of complex organisation.

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I.S. Shaffer (Naval Air Development Centre)

Mr. Chairman, I want to respond to the statement made that "Corrosion in electronic systems is trivial when compared to the corrosion damage that occurs on large airframe parts." Although it maybe true that the replacement cost of a small electronics component can be considered trivial, the resulting degradation in equipment performance or its complete failure due to a corroded component can be significant. Data compiled by the Naval Safety Center show that corrosion of such a component can lead to the loss of an aircraft or serious injury to its occupants. For a total of 150 safety-of flight mishaps attributed to corrosion in a six month period,51 were caused by corrosion in electronics equipment. Cited were 28 connector failures, 17 switch failures, and 6 failures caused by corroded terminals. In another report the Naval Safety Center disclosed that 29 of 77 reported incidents, involving the inadvertant jettison of live ordnance including bombs, rockets, and missiles were caused by corrosion and moisture in the electrical connector that mates the pylon circuit to the wiring on a front line fighter aircraft. The terrible consequences which could occur certainly make the corrosion of electronic components not a trivial matter.

Mr. Chairman, I also would like to present some recent Naval aircraft corrosion maintenance cost data. These data show the direct maintenance manhours expended in treating corrosion on 11 of the Navy's front line aircraft types. The numbers are based on the maintenance performed at the first two levels of maintenance, the organizational or squadron level and the intermediate level. Data for the third or depot level conducted by the Naval Air Rework Facilities are not included. The total labor cost for the one year period Jul 79 - Jun 80 was $64,690,000.

COST OF NAVAL AIRCRAFT CORROSION *

AIRCRAFT	CORROSION MAINTENANCE DMMH/YR (thousands)	CORROSION MAINTENANCE COST (thousands)
A-6E	445	$7,414
A-7E	811	$13,511
F-4J	491	$8,180
F-14A	498	$8,297
EA-6B	190	$3,165
E-2C	130	$2,166
P-3C	346	$5,764
S-3A	431	$7,180
SH-2F	174	$2,899
SH-3H	262	$4,365
CH-46F	105	$1,749

Period Jul 79 - Jun 80 Labor Rate: $16,66

*Includes Organizational and Intermediate Levels of Maintenance Only

M. Doruk (Middle East Technical University)

I would like to raise some questions that would be interesting also from an aircraft operator's point of view. Are we in agreement on some threshold requirements for materials and also design practices, which would enable the buyer to include the corrosion resistance of aircraft in this evaluation? This approach would also provide the advantage of forcing manufacturers to meet these requirements.

Another question which arises from the experience of users in Turkey is concerned with the frequent replacement of some critical parts. In my presentation on the aircraft corrosion in Bandirma, I emphasized the rapid damage of the vertical stabilizer attach angle (Alloy 7075-T6) owing to stress corrosion cracking and exfoliation corrosion. Some of the presentations in this session showed that the alloy 7075-T6 exhibits the least resistance to exfoliation corrosion. Considering the fact that the replacement of such a part is very expensive and time consuming, my question would be whether this material could be replaced with a better one. We would appreciate to hear about the experience of other aircraft operators.

V.C.R. McLoughlin (Royal Aircraft Establishment)

One must use the best possible means to reduce, when I say reduce corrosion, you can never stop it completely as long as we live with aluminium. But you then have to come to the question: how do you do this? What restrictions do you place on the manufacturer? Do you say "You shall not use magnesium alloy"? Do you say "You shall not use cadmium plated steel fasteners"?

I am very doubtful that you can prohibit. I think the future improvement lie in the hands of the customer, and, again, it is dangerous to tell the customer what he should be asking for. We have so many different approaches: basic processes like aluminium alloy pretreatments, for which the philosophy differs drastically. In the U.S. you mainly use sulphuric acid anodising and you seal it. In the U.K. we say better to use chromic acid anodising, better not to seal it.

Its so difficult to provide really one-fix answers to corrosion protection. I'm glad that KLM are pressing for improvements, and I share their optimism that things will improve. But I'm afraid we're all in the market for bargains: we all like to go to a sale and buy something which is marked down. And I cannot see any customer every time insisting on the best possible fix - that of getting rid of those steel fasteners - because its going to cost him an extra half-a-million pounds for his aircraft. The other guy will come along and say "I'll give you lower operating costs by using lighter, stronger materials, which may corrode a little bit more but, really, we know how to stop it." This must be a very major pressure.

All we can do, I feel, is to advise, and it is up to the customer to choose. And I think that the customer is beginning to realise far more now than five or ten years ago. But it is in the hand of the customer.

And one point that was raised on when do you replace a susceptible material by a non-susceptible material. This, again, it is up to the aircraft designer. It is up to the customer to feed back his requirements for a fix on that aircraft, maybe to suggest to the designer that he should be using T76, T73 tempers, and for the manufacturer to agree to give you the fix. That's the way that the feedback loop should be operated, and I think it is operated in the U.K. fairly well, although I'm sure a lot of operators do their own fixes. But it is strictly illegal, it is the manufacturer's responsibility to modify the structure in any way. And, again, this should encourage the manufacturer by making him give you an answer to your problem. But it is not one that I think the operator should take on himself. Thank you, Mr. Chairman.

D.W. Hoeppner (University of Toronto)

Mr. Chairman, I'd like to thank all the speakers for their enlightening remarks. I would like to start by saying if I were attending a manufacturers' meeting (which I frequently do) I would hear them say "The users don't know how to use our airplanes". And so I'm a little suprised to see the behaviour here somewhat like that immature behaviour of the manufacturers, where they're making the airplanes to meet your needs.

At Lockheed, when I used to be there, we had, albeit with its shortcomings, a corrosion control programme which was implemented in 1948, albeit it is still evolving. It is evolving because we, as a collective community of beings, have not been specific with respect to the way we will categorize corrosion ranking of engineering materials. When we get engineers at companies or laboratories, to educate them on the needs of aircraft among other things, we give them a list of commandments. One of the first commandments we give them is "Thou shalt have no corrosion."

Now, I would like to suggest that there are some illusions amongst this audience about fatigue. I have devoted approximately twenty-five years of my short life to fatigue design. I currently conduct programmes at the University of Toronto for numerous aircraft companies and for the Federal Aviation Authority and for many engine manufacturers. Every place where fatigue has a time dependent characteristic, we don't know what to do. We are scurrying to develop empirical formulae or algorithms by which we can establish fatigue design property allowables to put in handbooks which we currently do not have. That includes the United Kingdom, Europe and North America. And I am doing extensive work with members of the United Kingdom on this very problem. So I don't understand how people can say we have fatigue in hand, when we in fact do not. We have it in hand when we can utilise procedures which assume time-independency of the fatigue phenomena. Now, any time we get into time-dependency, as in corrosion or corrosion fatigue, we have a very significant problem on our hands. We have analogous problems, of course, in wear, creep and corrosion itself.

So I would like to suggest for future deliberations of this body to give the designers the following information. What quantities do you want us to measure that relate to our configuring our aircraft so they can have no corrosion? We designers like to have numbers not words. We would rather see numbers in terms of either today's stress, strain or stress intensity parameters. So if you could please provide us with the standard test procedures by which we may evaluate and characterise materials, characterise system joints, characterise coating and protection systems of various kinds discussed in many of the papers, and provide us with the specific test procedures and the specific ranking procedures and evaluation procedures, I'm sure we could all move forward with much greater haste and stop pointing fingers at one another. Until we have those things I suggest we will have more meetings like this, where we say "It is the designers.", and the designers and manufacturers say "Its the maintenance and operators".

So I would like to suggest that we quantify exfoliation resistance by a material property design allowable, and not by a general exfoliation characteristic which we have trouble designing toward. In that regard I would like to further query the members of this audience: how, in the future and as much today as myself and others in this audience and throughout the world are concerned with the education of engineers both in manufacturing operations and design operations and in education, we improve the education of design engineers for corrosion.

The problem that we have here is that the engineering educational community throughout the world does not comprehend the importance of corrosion in educating aerospace, mechanical, chemical, etc. engineers that are going to go to work. We would be extremely appreciative of a significant voice coming from NATO, and particularly this group, that could provide us any direction in formulating educational policy for engineering and training of engineers. We heard about training of maintenance personnel, I agree that's important. But we would like some guidance, and I would appreciate any guidance you can give us. Thank you for your kind attention.

T.W. Heaslip (Aviation Safety Bureau, Transport Canada)

I have some twenty years investigating military and civil aircraft accidents and I have a few suggestions from that background. Number one, I'd like to point out that I could probably get up and give a two hour dissertation on accidents which resulted from corrosion, both in the military field and in the civil field.

One of the points I'd like to make is that over the years, after we have accidents and when we're dealing with the aircraft manufacturer, I hear the same complaints over and over again. We point out other incidents and examples of similar cases that occurred before the major catastrophe, and the manufacturer invariably says "There's been no feedback from the users." And I'd like to find out, maybe its a bit naive, but are you going to, for example from this meeting, send the proceedings to all of the major aircraft manufacturers in the world. Because its only through feedback, as David Hoeppner pointed out, that the materials and processes and corrosion teams and the aircraft manufacturers can gain from the experience out there in the real world to improve their product.

J.J. de Luccia (Naval Air Development Centre)

A couple of points. I'd like to say a hearty amen to David Hoeppner's plea for engineering education with regard to corrosion. I think that a major step would be to have the educators realise how important the subject is and make it a required course for chemical engineers, mechanical engineers, as well as materials engineers. I think that's item number one, and perhaps we could send the proceedings to some of the major engineering universities. This could be a step in the right direction.

With regard to the controversy as to where do you best control corrosion: is it in the design stage; is it in the maintenance stage? Dr. McLoughlin correctly pointed out that you could only really reduce corrosion, you can't eliminate it. So the pessimistic observation that we must prevent it and this is the only way - and if not, all hope is lost - is perhaps a little bit too grim. As long as you have a negative change in free energy you're going to have corrosion. When you write the equations you get a negative change in free energy.

I think it's best to control corrosion at the design stage, but being realistic we realise it's going to occur, the user's going to have to live with it. So I don't think that we should just throw up our hands and say "If we don't prevent it in the design stage we must say that all is lost." I think there is such a thing as control. I think there are products that are coming out: better paints, better corrosion control techniques, procedures, compounds, new thoughts. We have been supplying the sailors, Mr. Browne can attest to this, with products that are making life a little bit easier from the corrosion control standpoint.

So those two points: I think that we can't really say we have an answer in the maintenance community, nor do we have an answer in the design community. I think it has to be a combination of the two. I think that at the root of both of these is education. As David Hoeppner pointed out, let's start to educate the engineers that do the designing and maintaining. Thank you.

R.G. Mitchell (British Airways, Structures Group)

In don't think the operators have ever expected to receive an aeroplane and not have to do any work on it whatsoever. I think what we're complaining about is the sort of problems that we've seen in the past that are repeated, which keep on continually appearing each time we get a new aeroplane. As KLM mentioned, we have the basic specification in which to specify the sort of protection, the sort of performance we expect out of the aeroplane. And we're told this time for example "No corrosion under galleys. We've fixed it.", and three years later we take them by the hand and we say "Well, there you are." and there's much head scratching.

It is the recurring problem that we are really trying to home in on. Each and every operator has his own corrosion control programme. And this is based on, and I think its spelled out in some detail in the paper I've presented. It is really based on how you operate, where you operate, and the operator does from his own large experience go round ensure that the coatings are intact, ensure that his paint schemes aren't deteriorating with hydraulic fluid spillages and so on. He tries his damnedest to keep the aeroplane free from corrosion.

The comment was made at the back about feedback. We have been feeding back information to manufacturers for such a long time. I'm not going to quote manufacturers, but we operated a model of aeroplane, and I know that other people fed back information on corrosion to the same manufacturer; and when we got the bigger brother we thought it had all been fixed. That aeroplane, the later model, was far worse in terms of corrosion performance than the one that we'd been feeding all this information back. So what happened to that information?

As far as the IATA guideline is concerned it is purely guidance material, and I don't think it can ever be looked upon as telling anybody what they should do and what they shouldn't do. It really is a collection of experience to say "Look, if you do it this way then we, the operators, stand a reasonable chance of having relatively trouble-free aeroplanes in the field, coupled with our own control programmes once we've got the aeroplanes in operation."

We don't go into the depths of the sort of things that you mentioned. I don't think we would have the knowledge to say that you shall or you shall not use these things. But what we do see in there is that "Thou shalt not use 2020 or 7079 aluminium alloys." And we don't have to tell the manufacturers that they shouldn't use 7079-well, I hope we don't. We say that our experience with magnesium alloys has been disastrous and we don't want to see magnesium on the aeroplanes. These are the sort of things that are contained in the document. Thank you very much.

T.F. Kearns

I think we're very close to the heart of the problem. When you say that you've been feeding back information and it has not been reflected in future aircraft, what this really says is that the users have not been convincing or the people that you have been feeding the information to just don't know how to do this. Those are about the only two possibilities. It's my opinion that the information has not been convincing.

I spent a lot of time in the U.S. Navy. For years we as the engineering and R and D community tried to persuade the project managers, who bought the aircraft, that they should use certain engineering practices to prevent corrosion. But it was only after five years of continual telegrams from the fleet, which would say things like "Please stop sending us these bio-degradable aircraft. We've spending twenty-five ......" A pile of telegrams that high would come in each year. Now, that message finally got through to the higher levels who spent the money to buy aircraft. It got through to the R and D community, and it led to the development of the T73 heat treatments, to the 7050 and 7010 alloys. I won't be specific here. We now know how, if we want to, to specify aluminium alloys that will not give you stress corrosion problems. And the answer to Professor Doruk's question is quite clear: just change the material to 7050. That's an answer, we all know that now.

So I think that it would be well for us to think of how we do in fact get this message across more effectively than we've gotten it across in the past. We all agree, but the message still has to be driven home so that we can in fact achieve our objectives. We still have the question, in accordance with Dr. McLoughlin's remarks, how far do we push them? Do we in fact prevent steel fasteners? Its my opinion that we should not, but there is some level that we should insist on reaching. And it may not be the same in military and civil aircraft, but there should be a consensus on that.

G.T. Browne

I'd like to say a few things from the operating side of the house. The U.S. Navy operates its airplanes all over the world, and we see a lot of problems. We live in, I guess, the most corrosive environment you can have - salt water. Even when the weather is nice, on an aircraft carrier that's proceeding through the sea we have what we call a bow wave. It rolls off the front of that ship. If we have even very light wind, the wind will pick the salt up and deposit it all over the ship on the aircraft.

The question of washing airplanes came up. We wash ours twice a month, at sea and ashore. We quite often wash them more frequently than that, especially if they get exposed. I mentioned a thing in my paper about an energency reclamation programme, which consists starting by washing the aircraft. And then it goes through into several other things, removing electronics and washing them in soap and water and drying them, when they get wet. It works.

The question on how long does AMLGUARD last came up a few minutes ago. Our requirement is each fourth washing that the AMLGUARD be replaced on the airplanes. That is in wear and erosion type areas. From personal experiences I've seen AMLGUARD last up to three years in some applications. If it's put on and allowed to dry hard it will last.

A question about honeycomb came up. I've been in the aircraft maintenance business for about forty years, thirty-two years of it in the Navy, and we started out, I think, with a material called "METALITE" in the F4U airplane, the Corsair, in World War II. It was a couple of sheets of aluminium, very thin, with some vertically mounted balsa wood in between it. Well, it used to get wet, and the wood would rot, and it would cave in.

When we got to the honeycomb, for which we used nomex and aluminium both for the core, most of the failures that we've seen in honeycomb in the U.S. Navy have been caused by water - water leaking in to the honeycomb - causing corrosion, causing a debond from the two skins, and a potential failure. Usually, this occurs when the airplane is flown at high speed and you get a harmonic vibration: it'll break. When it comes back it looks like some big animal has bitten a chunk out of it. We have lost nearly complete surfaces. On the F4 stabilator honeycomb we have had airplanes land on aircraft carriers with the entire section gone, with no real noticeable flight control difference reported by the pilots. The pilot would get out of the airplane and say "Gee, I wonder what happened there." And he had not really known that he had lost a component. It does require replacement, but these are things that have really happened in a real world. And I've seen them. Okay, the floor is open again.

D.M.F. Bright

Nothing that I've heard, perhaps, at the meeting so far leads me to conclude that we don't have the basic knowledge. The past discussion seemed to indicate that the problems are well known; and the solutions, in principle, are in fact also well known. I was talking earlier on today about the Aviation Publication 970 design requirements, and I'm sure others exist in the U.S. Mil. Specs., and so on. I consider these are very good documents indeed, and, if followed in the spirit in which they're intended, ought to do a great deal for our new generation of designs. So its a question of trying to implement these specifications.

Now this, of course, is a problem which involves, I suggest, cooperation. And I wouldn't like anyone to feel that this should become a users-versus-designers sort of head-to-head confrontation, because its not. The user must be involved in helping to improve these already very effective specifications. Then we come to the intelligent and systematic application of them in design. Now, as I've said before, this must be a matter for the Design Authority himself. But there are, again, reasons for an input to be made by the user again. In many cases he may have a project team or some kind of linkage between his Engineer Authority and the Design Authority in order to try and guide the application of these specifications.

There are special cases with new designs which need to be thought about. One I'd like to correct any impression I gave earlier on - one which needs special attention in the new generation of aircraft - is their greater vulnerability to avionics corrosion. Because there is no doubt about it: if we have a systems failure as well as a structural failure we can equally well lose the aircraft.

But perhaps one of the major obstacles in the end, and this comes back to the user again, is the question of how much money are we going to pay. Are we going to go in for titanium rather than steel? And I must confess here that the user does to some extent pay lip service to life-cycle costing and is not always fully prepared to pay this higher price for the higher quality design in the first place.

So I'll just conclude there by saying that I think there's got to be this very strong cooperation on developing the specifications to the highest possible standard and then actually implementing them when we come to the new design. Thank you.

J.R. Lee (Westland Helicopters)

I feel that it is about time that a constructor dares to stand up. I speak really as a metallurgist in a company that primarily makes helicopters for operation by navies round the world. So we know plenty from the customer of the problems of corrosion.

One or two points I would like to make. First, a follow-on from Wing Commander Bright's last comment. I find that specifications for aircraft now are written with very stringent requirements, including corrosion. But to take these to the optimum, for example to use titanium fasteners as Tom Kearns has mentioned, does cost money. But what happens is you put up a proposal to meet that - and the order goes for an aircraft that is perhaps designed twenty years ago, full of corrosion prone features, because it is cheap.

I believe there is a major lack of communication between the user and the Treasury, whatever country you're talking about. The Treasury has so much money, it wants so many aircraft. It divides one by the other, and that decides the aircraft it buys. Why has it so little money? Because its spending so much on correcting the corrosion on its old fleet! And I would be quite willing to guarantee that in twenty years time there will be another meeting saying the same thing: because the customer is still buying aircraft that are known to have poor corrosion features, because they're off the shelf and they're cheap. I've heard I think in the last year several lectures by military personnel from the operations side, talking about life-cycle costing. All very enthusiastic. But its not yet trickling down to the people who place the orders.

Changing completely, I think one aspect that I haven't heard at the sessions I've been able to attend is the importance of the quality of application of the protective treatments. I've heard a great deal of criticism of the designer, but however good the designer specifies it, the performance depends on how well it is applied. If a good chromated primer is put on well pre-treated, freshly anodised material it will last a lifetime. If there is a long delay and some dirt in between, most of its efficiency has gone. There has been a great point made of the importance of interfaying. But interfaying is only effective if it is complete. If there are gaps in the interfaying you are no better than having no interfaying at all - because you have a point to start corrosion. At one stage I introduced spot radiography on an aircraft, just to take pictures of interfaying to show the operator, to show the areas he was missing. And it is quite enlightening if you do that, to see how variable the coating is if you are applying hand - applied interfaying.

One different point again. The current specifications for military aircraft are coming out requiring very low scheduled maintenance requirements. I wonder if we are going too far in this respect for military aircraft that have a relatively low flying rate. Particulary thinking of mechanisms, mechanical systems in aircraft, I feel it is better to spend a little more time doing regular maintenance - the grease gun, the oil can, the AMLGUARD - than wait till it fails and have unscheduled unserviceability. And for a military operator I feel it is better for the squadron personnel to be spending their spare time on husbandry rather than doing nothing. After all, the military operator must have staff available for the time that it is needed. This, I think, does not apply in the same way in civil operations.

Last comment: there have been questions of what can we do to educate the designer. My belief is the very best thing you can do is to take a few of your senior structural designers and either put them on a carrier or put them with a squadron operating from a jungle clearing in Africa!

G.T. Browne

I'd like to make an answer to that last. We do this in the United States. In fact I have taken two or three groups out myself for a week or ten days on a carrier and let them see what happens to their product. They do get banged around a bit, of course, according to what type of weather you see. And we do have a standing invitation to anybody who would like to see a carrier: just walk aboard one at COMNAVAIRLANT. Take a tour and walk around (POC Mr. G.T. Browne).

We have also exposed a lot of our engineering folks, in fact I have taken Mr. Shaffer out for about ten days on an operating aircraft carrier. I think it was his first trip out on one, so that he could get a first-hand view of where the R and D work was needed. And this is open, in the United States.

There is one other difference I'd like to address, that Mr. Lee made about the military and civilian difference. There is definitely a difference. Most of our civilian mechanics are Airframe and Engine licenced, by the FAA or the various country's agencies that licence aircraft mechanics. In the military we have very few people of this type. We do have some, but we have very few of them.

We have a continuous training programme. We get your sons and daughters out of high school or out of college, they come into the military - its a whole new world. And its a whole new technology in a lot of cases. I think that the military technology moves a lot faster then the civilian technology does. And these young folks have a heck of a time catching up to where we are. And, of course, the operations are quite different. And I don't really concur that we fly less. We don't fly a scheduled airline-type flight. Military airplanes are scheduled fairly heavily during an operational period. And they stress full systems readiness: if a combat airplane cannot go out and do its job, there's no use launching it. You might as well let it sit on the deck, because you haven't accomplished anything other than flying the airplane. Each flight has got some type of mission attached to it. And if the airplane can't perform it, due to avionics corrosion or corrosion in some other part of the aircraft, you might as well not launch the airplane.

Anybody else got any comments right now?

Dr. Selcuk (Middle East Technical University)

Mr. Chairman, I'd like to make an attempt to change the tune of the discussion, if I may, and come to the nitty-gritty aspects of protective measures. Yesterday we have heard some new attempts - at least, new for us - on the protective measures as far as the paints and plastic coatings are concerned. And one of them was water displacement paints, that Dr. De Luccia explained. My inquiry is that how does it function, that WDP? As far as I can understand it was washing off the seawater and it was painting after that: you know, it was coating a protective coating. One would suspect that it would contaminate as it washes off the seawater, and the protective property of the WDP will diminish as it goes on painting the surface. I'd like to hear Dr. De Luccia's comment on that, please.

J.J. De Luccia

What was shown yesterday in the vugraph was an experimental attempt at looking at the ability of the product to displace water. It is not intended to go out on the aircraft carrier, on the airplane, and paint over a specifically wet surface. However, realising that we might not - in crevices and in areas where there are fasteners - we might not get all the water out, and we might have to touch up while in operations, we've developed this product. This product does displace the water, it does displace the salt in the water, and as a consequence the surface that the point ultimately deposits on is the metallic surface. We have found that the adhesion is good, it has not washed off. We are sort of encouraged by what we see so far. I have to say that we supplied Mr. Browne with about ten gallons of the stuff?

G.T. Browne

No, it wasn't quite that much.

J.J. De Luccia

Well, how many airplanes did you paint?

G.T. Browne

This paint was assigned to an E-2 squadron that is deployed in the Indian Ocean right now, and they should be returning shortly. And we will have a look at the airplanes at that time. They have supplied reports - spasmodically - to the Centre, and we're looking forward to seeing what the airplanes look like when they return to the United States.

J.J. De Luccia

The reports that were supplied so far are favourable.Now,again, I want to clear any misconception that the vugraph that I showed was the correct manner in which we apply this paint. It is not: it was merely an experimental procedure. Thank you.

G.T. Browne

To further answer Dr. Selcuk's question, we are using the paint for routine touch-up of the aircraft, when required. It was put out that way not as an experiment but just to be used and then followed and watched. We've also done this with AMLGUARD. We assigned two of our F14 airplanes several years ago to a six months' deployment with no paint applied to them, only AMLGUARD. The results of that experiment were: no corrosion, not where the AMLGUARD had been applied.

Do we have some more discussion? Yes, sir.

D.W. Hoeppner

So far we have heard that there's going to be, apparently, a corrosion design handbook coming along, or potentially.. I assume that that will involve both corrosion design and prevention methods, and then material property allowables, etc.

But both Dr. Schütz and Professor Doruk and myself have queried, because, I think, our collective great concern about standards, specific test standards for ranking materials and structural configurations, specifically joint configurations, etc., for their corrosion resistance, for a specific kind of corrosion in a specific environment at a specific temperature regime. To re-echo, if I may, both Dr. Schütz's question and Professor Doruk's and my own: could you please inform us a little further on what standards do exist? Are standards in the process of development, like the stress corrosion standards for example where we involve pre-cracked specimens in environments, for the different forms of corrosion discussed at this meeting as well as others -exfoliation, filiform, corrosion fatigue, fretting fatigue, etc.? How are the ranking procedures being developed to evaluate the materials and structural joint configurations? What comparative tests are available? Or are we to continue to use the basic go-no go type procedures: yes, there is corrosion - no, there is not corrosion, etc.?

And a third part of my inquiry here is: if we accept the view that we must always prevent corrosion, we probably would end up designing no aircraft, or no hydrofoils. So, as several people have said, that's probably not likely. So we will continue that pursuit. But, to echo again Professor Doruk's suggestion: what progress is being made toward evaluating materials and joints for thresholds relating to their corrosion resistance? I haven't heard any discussion of his specific inquiry.

W. Wallace (National Research Council)

I think we all know very well that AGARD is not a standards organization as such, and I think the truth of the matter is that we're doing nothing at the moment in terms of developing standards for corrosion evaluation of aircraft materials.

I think before we started we all knew very well that corrosion was a major problem, and that if we were prepared to spend the money and the time, we could live with it. One of the problems, of course, is communication. AGARD has tried to respond to this by embarking on this series of corrosion-related handbooks. We have two handbooks underway at the moment. The first of these is attempting to document the corrosion problem by providing good information on current problems as they're experienced by operators. We've having tremendous difficulty meeting our commitments with these handbooks, because we do not have the support of the corrosion experts. I would appeal to all of the people who are interested in these problems to attend the meeting of the Corrosion Sub-Committee this afternoon. We've been working on this for about three years and we're not much further along. We have a lot of information, but we need the help of the experts to put the information together.

In terms of costs, it seems we have problems. We have difficulty convincing the procurement people that its worth imposing strict requirements. I think we're only going to convince these people if we can put together a well-documented case. We've also started looking at this problem, but again we need the support of the operators and the corrosion experts in order to complete these exercises. And right now we're short of this support. Again, I would appeal to you people to come and join AGARD to achieve some of these objectives.

V.C.R. McLoughlin

Test methods - its a very difficult area to give any complete answers on. Starting with stress corrosion: yes, the ASTM procedure is an excellent one. Alternate immersion testing appears to relate very well to experience of alloys in an aircraft environment - but with some reservations. Our own experience, for example, is that 2024-T3 is the worst alloy one could conceive of from the point of view of stress corrosion. And yet the operators wouldn't say this - 7075-T6 is far worse. But the test does show that its a susceptible material, and I think that's as far as even an excellent test method can go: it holds a very big question mark against the material. And I think that of all the test methods for aircraft-related materials that particular test has been used for many, many years and is believed to be an extremely good test in relating a laboratory test procedure to operating experience.

For exfoliation corrosion there is an ASTM test procedure which is again extremely good in relating most alloy performance to that which occurs in practice. And yet we have taken pieces of aircraft which have shown severe exfoliation, I must say geriatric aircraft, and when we've put the same material in the test solution there has been no exfoliation. So again one has to question whether you can be dogmatic in saying "These materials shall not be used". Any test method can only be used as a guideline. In the U.K. we have tried in our documentation in Aviation Publication 970 to use the operators' experience, the manufacturers' experience, to advise on which materials should be avoided, and even to go to the extent of saying which materials shall only be used with the customers' agreement. But I don't think one can go very much further.

When it comes to paint performance, this is even more difficult. Within AECMA the test procedure which has been adopted is an alternate immersion test based on the SIETAM cabinet, where a scribed test piece is immersed for two hours and then unimmersed in a high humidity environment. I think its at 35°C and the immersion is in a saline solution at pH 8. And again, this seems to give very good correlation between experience of the performance of paint schemes on aircraft and their performance in this test environment. But we really don't know whether novel paint schemes, with novel inhibitors, will react similarly. Its a very, very difficult area, and one where we feel almost unable to advise the designer much further than we do at the moment, in giving guidelines and only being damning of materials where experience has shown them to be dangerous and materials which really should be avoided at all costs.

H.M. Burte (AFWAL/MLL, Wright Patterson AFB)

Listening to the last discussion prompts me to raise an issue about the relationship of corrosion science to corrosion technology. This conference has been doing an excellent job of speaking to the very applied nature of the corrosion problem - the new processes coming out, the need to do better things in the engineering of our systems and the need to learn from experience. Other conferences or meetings often have university people talking about the chemistry of things that may not have to do with real life corrosion. Is there a connection between these?

Speaking to this: about five years ago one of my colleagues and myself undertook an analysis of the health of the Materials Science base in the Unites States from the viewpoint of the needs of the Air Force and aerospace (at the start). And here's what we came up with:

APPLICABILITY TO AIR FORCE OF MATERIALS SCIENCE BASE		
INADEQUATE	MARGINAL	ADEQUATE
Processing science	Metallurgy	Solid state physics
Surface physics and chemistry	Ceramic science	
	Polymer science	
NDE science	Mechanics	
	Thermophysics and chemistry	

Let me explain it to you and first state what we were not evaluating. We were not considering the sort of applied work that is solving current problems or empirically developing something that seems to work and then putting it into use. Nor were we considering what is often called "truly basic" research, where the motivation is only the exciting new knowledge which can be gotten.

We were attempting to evaluate the extent of need driven fundamental research, which although quite fundamental might be expected to find some use or application within five or ten years. The way we did this was an iterative process of talking to many people who might want to use fundamental research, as well as to the producers of fundamental research (I won't go into the details, I can talk to you individually if you're interested). An extensive series of discussions identified areas of need in fundamental research - where there were big gaps; where there were many, many subjects where it seemed very few people were doing work that could solve, or have a significant impact on practical problems in five or ten years.

We did that first for aerospace in the United States. Then I talked to enough people in energy and transportation and other fields like the normal productivity of consumer goods, to find out that our conclusions were applicable to the entire economy. I also, in the last few years, have had the opportunity to talk to many people in West Germany, in England, in France, and in Sweden, and to find out that in general they agreed with the conclusions I am showing to you.

Now, posing it to you, do you agree with these conclusions? What do they mean?

The fact that solid state physics is "adequate" doesn't mean that one shouldn't do more research in the area; it just means that it is a popular area and there are not many problems where at least a few people aren't working - there are not big gaps. It is surprising that there are big gaps in surface physics and chemistry - since it is an area in which a lot of people have been working particularly during the last ten years, as many new experimental techniques for characterizing surfaces became available. Many, many people are doing truly basic research on the nature of surfaces. But when this work was analyzed from the viewpoint: how much work was going on that might in five or ten years apply to definable problems, the answer was very little. (One reason surface physics and chemistry was shown as "inadequate" was because of the apparent lack of work going on that might be applicable to many complex degradative processes like corrosion or wear.) Is this still the case?

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G.T. Browne

Thank you. Do we have some more comments?

T.F. Kearns

Mr .Chairman, we're approaching the end of our conference. I think it would be well for us to try to be as specific as we can in making recommendations, if we can reach a consensus on recommendations as to what we as a community now, of users, designers and manufacturers think can be done, particularly those things which AGARD may serve some function in. And in this connection, since the users are here, I would like to hear whether there are any views from the operators, from the users, as to what would you like to have done? What do you think that AGARD can do to help, keeping in mind that AGARD primarily is likely to be able to help in the communications field rather than in specific specifications or analysis of specific technical problems.

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It would seem that there is a forum whereby the requirements for military airplanes are fairly well handled. The users and the constructors seem to have a forum whereby they can collectively review their problems, and so on. Because I think in the civil field each and every operator goes to his individual manufacturer with his individual problems. And yet when you look at transport aircraft I would suggest that the military transport and the civil transport are very, very similar animals, and the requirements are therefore very, very similar. There's a wealth of experience available within the airlines, and perhaps the handbooks that have been suggested would be absolutely invaluable to some of the smaller or the less experienced airlines. So is there any way that the airlines can be associated with the AGARD movement? I welcome your comments on that.

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But the major problem right now is finding some mechanism for processing this information and getting it into print, where it can have some impact. We want to get a message to our Treasury people, the people who make the decisions to buy. We want to get a message across to the manufacturers, because if we talk to them collectively as a body, they will listen. They will not listen to some of the smaller countries, possibly, if we go individually. But I think one of the useful things that NATO can do is put all of its member countries together and allow then to talk to these different groups as a large and powerful body, we hope.

And so I would again appeal to people in the audience who have an interest in these matters to volunteer to help us to do the work. The Panel is a relatively small group of people, and like everybody else we're all busy. We need help to sort through the information, to analyse it, and to present it in a proper fashion to the audience we've trying to address.

G.T. Browne

We've had a couple of recommendations, and one keeps coming back. Our military procurement spec. for naval aircraft is pretty well updated and a pretty good document. However, to convince the procurement people that its cheaper in the long run to buy quality than quantity is a recommendation that I would like to make to the AGARD Committee for presentation to our Congress in the United States, because they are the people who fund the procurement of military airplanes. I'm sure that our other countries that are represented here have Bodies and Treasuries that do the funding and somebody telling them who and how much they are going to be able to fund. I would, for one, be willing to volunteer to help put this together from our point of view in the U.S. Navy.

Do we have some other folks that are interested in this?

T.F. Kearns

I see a common theme in the last several comments. And that is that we might recommend to AGARD that they can serve a valuable communication function, or that they may cause this to happen. The creation of a forum for exchange of views among the users, for example - the users in the civil and the users in the military across the NATO community.

Such a forum would be more forceful because it reflects a wider base. AGARD might facilitate communications between the operators, the users, and the engineering control people. The forum we have today is not such a communication. What I'm talking about is a small number of people who sit around a table and decide what it is that the users want to see changed in the engineering requirements.

We could ask AGARD to help, and I think I see the need for this, actually there are some plans to have the engineering control people in the different countries talk to each other. I note the U.K. likes cadmium plating, the United States likes aluminium: U.K. uses acrylic, United States uses polyurethane. Is there a possibility of collecting the totality of good recommendations (not implying that we're writing an AGARD spec.) just the technical information from all of the nations, collecting that? Some of that is, in fact, being done in connection with Volume 2 of the Handbook that Dr. Wallace spoke about.

We then have the communications between the engineering control people and the people who buy aircraft. Those are specific - the people who buy aircraft are usually one-time project officers. But nevertheless the communications there, I think, could possibly be helped by AGARD. A strong recommendation like this might in fact cause the Panel to create a variety of different activities, none of which is a major earth-shattering thing, but each of which may in fact contribute to the kind of actions that are being recommended.

So I think the direct answer to Mr. Mitchell's question is "Yes, AGARD is flexible enough so that there are mechanisms whereby civil operators can be tied into military activities in AGARD, for our joint benefit.

C.R. Pye (RAF, Swanton Morley)

We've heard extensively that corrosion is expensive, and a lot of people have quoted figures at us. And we've heard we need to buy quality if we're going to reduce life-cycle costs. But in my opinion the missing link that we haven't heard is how much extra a design without corrosion would cost us. We can't make these life-cycle comparisons unless some designer says "Well, you can have this aircraft today, at this cost; But if we convert it to corrosion-free, or as essentially corrosion-free as we can make it, it will cost you so much more." And then as a Treasury man I could work that out across the life-cycle. Do we have any more comments on that?

G.T. Browne

I'd like to say something on that, and I agree with you. I know exactly what would happen if you would present this to a Body that is holding dollars. The first question they are going to ask you is "How much am I going to save overall?" That is not for the operator to tell them. That goes back to the R and D community, the engineers and the scientific community. I feel that they would have to say that the quality airplane over a period of ten years, or twenty years, or thirty years, is going to have to come up and cost you x number less dollars to maintain and operate than the one we're going to expend numerous manhours and replacement of components due to corrosion.

Components are very high priced, and quite often you have to remove and replace. I think we had a paper here yesterday talking about replacing components on civilian aircraft: large pieces which cost as much as $ 2,000,000 a copy. The $ 2,000,000, $ 3,000,000 or $ 4,000,000 that have to be expended by an organization to fix one, two or three airplanes could be eliminated, and that might be the cost difference between designing the quality or not. I don't know, that's something that the scientific community is going to have to tell us.

Are there some more comments?

H.M. Burte

I quite agree with both of you, but let me talk to the real situation. The conflict during the design and the trade-offs for a given system is like the following. Somebody will come in with some experience data ans say "Expend this much more and you'll save this." Unfortunately this is often based on pretty soft projections, difficult to prove; more qualitative than quantitative. If you are the program manager you have two options: a very hard projection - I can buy it for this much less; or a pretty soft projection that if I spend this much more, maybe I'll save this much more. Which decision are you going to make? You know which one!

We were attempting to evaluate the extent of need driven fundamental research, which although quite fundamental might be expected to find some use or application within five or ten years. The way we did this was an iterative process of talking to many people who might want to use fundamental research, as well as to the producers of fundamental research (I won't go into the details, I can talk to you individually if you're interested). An extensive series of discussions identified areas of need in fundamental research - where there were big gaps; where there were many, many subjects where it seemed very few people were doing work that could solve, or have a significant impact on practical problems in five or ten years.

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So the problem gets to be, I think, what Mr. Kearns was saying. To what extent can one project an experience base that is hard, a lessons-learned base - of perhaps only a few things to start - but that everybody firmly agrees on, and where there are convincing numbers. I think if you start there you can make progress, and that perhaps is a place where the AGARD community, by sharing experiences and therefore making them much more credible to the man who makes a decision, can perform a very useful function.

J. Fielding

I would like to comment on Squadron Leader Pye's plea for a little more information on the cost of reducing the corrosion hazard. In British Aerospace we did consider, approximately a year ago, what would be the extra cost of converting some of the old fashioned aluminium alloys to one of the improved 7000 series such as 7010 or 7050 or 7475, when the cost of that material itself may be increased by up to 20 %. And the way this comes out in the calculations is that the cost of material is only about 10 % of the cost of the airframe. When one considers the cost of all the systems, the cost of the engines, one particular fact which came out was that if we change the whole wing materials to one of these improved aluminium alloys, the increase in cost of the total aircraft would be about one-half of 1 %. So I would suggest that the cost of using improved aluminium alloys is, perhaps, almost negligible. And one can take this a little further, and consider the introduction of still more expensive materials (titanium has been mentioned) and while the costs are considerably more than the aluminium alloys, the increase in cost on the overall aircraft is still comparatively small.

I think, to change the subject, I would like to endorse very heartily something that Mr. Lee mentioned. I, too, am a materials engineer and I have seen the development of materials over very many years. And I have noted the attitude of mind of several of our chief designers. And we say to them "We now have an improved material. This will assist in combating corrosion. Will you use it?" I say it is a little bit more expensive, it is perhaps a little new; and the designer is often very wary of changing a material which, in his opinion, has possibly been satisfactory for his type of aeroplane. And we have very often, particularly in the United Kingdom, had a great deal of satisfactory service as regards corrosion (which we haven't heard very much about today, we tend to hear all the gruesome stories of corrosion). But I think the air force is getting the message over through the aircraft publication requirements we now have, detailed by Dr. McLoughlin. We have a very good code of practice which would not cost very much more to implement. I do feel there is still a failure on the part of civil airlines to get the message over very strongly to our chief designers: that they should be considering corrosion as a top priority, possibly second only to fatigue, and that we can spend a little bit more money, and we can spend a little bit more time. And they will not go immediately, as Mr. Lee suggested, buying the cheaper aircraft, the one that is immediately available off the shelf. I think these points are of great importance.

D.M.F. Bright

I'd like to back up what previous speakers have said about the possible function of the Handbook. I think it would serve as a very useful underpinning to demonstrate the need for the national specifications and the importance of implementing these specifications, and also perhaps avoiding the possibility of trying to strike a bargain by buying a cheap aeroplane from somewhere else.

The other point I'd like to raise is that in many cases we are living, possibly for twenty years, with aircraft designed to older design rules, and we know we have problems there. We have traditionally looked towards particularly the naval arms for palliatives for current problems, because they are the people who see those problems most severely.

I just raise the point as to whether there's any support AGARD can give, or should consider in the Committee meeting this afternoon, of any further work. We've heard about crack prevention compounds, and so on; whether that work could be supported by AGARD on a rather broader front.

G.T. Browne

Well, I don't guess there's too many objections to making that recommendation, so we'll work it up.

W. Wallace

Maybe I could say a few words before I formally close the meeting. In listening to these discussions one could easily develop a sense of growing despair. We have been flying aircraft for thirty, forty, fifty years - certainly for a long time, and corrosion problems have been with us all along. In spite of all the work that has been done to combat corrosion, the extensive documentation of corrosion problems, and the advanced technology that we have developed in the aerospace field, corrosion is still with us.

Many people have used examples of older aircraft in describing the types of corrosion problems experienced, and this is understandable since these are the aircraft where corrosion problems have had time to manifest. I suspect that in ten years or more, when we have longer operating experience with some of our newer aircraft designs, that the same problems will still be there. We seem to be repeating many of our earlier mistakes, possibly for short term financial gains, and there is evidence that we are even creating new problems. For example, we are constantly introducing new materials, for higher strength and stiffness, that do not necessarily lead to improvements in corrosion performance. We are introducing composite materials, that are bringing galvanic corrosion problems that were never experienced thirty years ago. And so I feel a sense of frustration that we are not making substantial strides forward.

However, since all AGARD meetings are, by definition, successful we should finish on an optimistic note and be satisfied that by working on corrosion research we will be secure in our jobs for a long time to come. With that comment I will thank you all for attending, and declare the meeting closed.

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14. Abstract

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