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Importance of periodic CPCP revisions in the evaluation and improvement of the program

NetJets Europe: a perspective from a business jet operator

(versão corrigida após defesa de dissertação)

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Resumo

No setor aeronáutico, a corrosão tem sido um problema severo e recorrente, principalmente desde a introdução de metais em estruturas e componentes nas aeronaves. Este tipo de dano pode afetar a integridade das estruturas, colocando em causa a aeronavegabilidade e a segurança da aeronave. A história mostra-nos numerosos e bem documentados acidentes de aviação, nos quais a corrosão foi um fator que levou a uma falha do sistema. Mesmo com importantes melhorias feitas, ao longo dos anos, na conceção e fabrico de novas aeronaves, incluindo o uso de materiais mais resistentes à corrosão, os operadores deveriam possuir um bom *Corrosion Prevention and Control Program* (CPCP) durante toda a vida da aeronave, alcançado através da experiência obtida pelo operador durante a operação da aeronave.

Esta dissertação expõe a importância de revisões periódicas do CPCP das aeronaves, no combate à corrosão. Esta pesquisa vem da necessidade de um operador de jatos executivos, a NetJets Europe, em reduzir custos de manutenção, relacionados com corrosão, e melhorar a disponibilidade das aeronaves.

Neste trabalho, é descrita uma metodologia segmentada e eficiente para uma revisão compreensiva do *Corrosion Prevention and Control Program*, a fim de melhorar a situação económica e operacional do operador. Foi criada uma base de dados com danos de corrosão, para cada frota da NetJets Europe, a fim de obter uma visão geral das áreas mais afetadas. Foi também realizado um estudo complementar, em termos de custos de manutenção e horas de trabalho, com o objetivo de encontrar as áreas mais críticas, estruturas ou componentes, que precisavam de ser selecionadas para uma extensa análise da causa do problema. Durante a análise da causa do problema, os fabricantes das aeronaves e os *Original Equipment Manufacturers* (OEMs) foram contactados para uma melhor avaliação dos problemas.

Os resultados obtidos mostram a importância destas análises, a fim de encontrar as melhores contramedidas possíveis, capazes de reduzir os custos de manutenção e melhorar a disponibilidade da aeronave, mantendo ou melhorando o nível segurança.

Palavras-chave

Corrosion Prevention and Control Program (CPCP), operador, manutenção, segurança, revisões.

Abstract

In the aeronautic sector, corrosion has been a severe and recurrent problem, mostly since the introduction of metals in aircraft structures and components. This type of damage can affect the structure's integrity, putting in question the airworthiness and safety of the aircraft. History shows us numerous, well-documented aviation accidents, where corrosion was a factor that led to a system failure. Even though improvements have been made, over the years, in the design and manufacturing of new aircrafts, including the use of more corrosion-resistant materials, operators should have a good Corrosion Prevention and Control Program (CPCP) in place throughout the life of the aircraft, achieved through the experience obtained by the operator during the operation of the aircraft.

This dissertation exposes the importance of periodic revisions of the aircraft's CPCP in the fight against corrosion. This research comes from the need of a business jet aircraft operator, NetJets Europe, to reduce maintenance costs related to corrosion and improve aircraft availability.

In this work, a segmented and efficient methodology for a comprehensive CPCP revision is described, in order to improve the operator's economic and operational status. A corrosion findings database was created for each NetJets Europe fleet, in order to obtain an overview of the most affected areas. A complementary study was also performed, in terms of maintenance costs and labor hours, with the objective of finding the most critical areas, structures or components, that needed to be selected for extensive root cause analyses. During the root cause analyses, the aircraft manufacturers and Original Equipment Manufacturers (OEMs) were contacted for a better assessment of the problems.

The results show the importance of these analyses in order to find the best countermeasures possible, which can reduce maintenance costs and improve aircraft availability, while maintaining or improving the safety level.

Keywords

Corrosion Prevention and Control Program (CPCP), operator, maintenance, safety, revisions.

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Acronyms and Abbreviations

A/C	Aircraft
A4A	Airlines for America
AD	Airworthiness Directive
AIPC	Aircraft Illustrated Parts Catalog
AMM	Aircraft Maintenance Manual
AMP	Approved Maintenance Program
ATA	Air Transport Association
CG	Center of Gravity
CIC	Corrosion Inhibitor Compound
CMM	Component Maintenance Manual
CPCP	Corrosion Prevention and Control Program
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FL	Flight Level
HFEC	High-Frequency Eddy Current
ISA	International Standard Atmosphere
LFEC	Low-Frequency Eddy Current
MPD	Maintenance Planning Document
MSG-3	Maintenance Steering Group-3
NDI	Non-Destructive Inspection
NLG	Nose Landing Gear
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
PCU	Power Control Unit
PTFE	Polytetrafluoroethylene
SAE	Society of Automotive Engineers
SB	Service Bulletin
SCC	Stress Corrosion Cracking
SRM	Structural Repair Manual
TICC	Technical Information and Communications Committee
US	United States
USAF	United States Air Force
UV	Ultraviolet radiation

Lay not up for yourselves treasures upon earth, where moth and rust doth corrupt, and where thieves break through and steal.

Matthew 6:19

Chapter 1

Introduction

1.1 Motivation

Corrosion is a natural process, that has accompanied humankind since the introduction of metals in structures and components in various sectors, such as infrastructures, transportation, etc. [1, 2]. The aviation industry is not an exception to this type of damage, and if undetected and untreated, it is a matter of time until corrosion starts to develop, and the metals return to their natural states [3]. In other words, corrosion is the nature way of reclaiming what is rightfully hers.

In aviation, this damage can affect, with a great deal, the normal operation of the aircraft owners or operators, especially affecting maintenance costs and aircraft availability. There are only a few detailed aircraft corrosion costs analyses available for consultation, most of them from military entities. Nevertheless, the ones that exist show us that corrosion is costly. In the US, it has been found, repeatedly, that around 30% of aircraft maintenance costs are related to corrosion [4]. In 1998, for all the commercial aircraft operated by US airlines (more than 7000), the total direct annual costs related to corrosion were estimated to be 2,2 billion dollars, divided in design and manufacturing (0,2 billion dollars), maintenance (1,7 billion dollars) and downtime (0,3 billion dollars) [2]. Another detailed corrosion costs report, from the United States Air Force (USAF), showed that, in 2008/2009, the USAF corrosion fleet costs were estimated to be 5,4 billion dollars [4]. The corrosion costs are not only associated with maintenance tasks. Corrosion can also affect aircraft availability, which contributes negatively to the operator economics.

Even though the economic impact represents an important factor in corrosion studies, safety is another and more important factor, with corrosion playing its part in numerous accidents or incidents, throughout the history of aviation. When corrosion strikes, the structural integrity is affected, and consequently the airworthiness of the aircraft is put into question, reducing the size, structural strength and fatigue life of the component or structure, especially when leads to an initiation point for crack growth [4]. However, it was necessary a catastrophic event, such as the Aloha Airlines Flight 243 in 1988, for the aviation world start to think twice when dealing with corrosion. From this accident, in a joint effort between Original Equipment Manufacturers (OEMs), aircraft manufacturers, operators and regulatory agencies, improvements started to be developed in corrosion prevention and control. In 1993, the Federal

Aviation Administration (FAA) published a guideline for a Corrosion Prevention and Control Program (CPCP) implementation into the operator's maintenance program which, through inspections, corrosion treatments, and preventive maintenance tasks, would be an important weapon in the fight against aircraft corrosion [5].

Over the years, improvements were also made in corrosion detection and prevention, with new and more effective nondestructive inspection (NDI) methods, and new and more resistant coatings and corrosion inhibitor compounds (CICs) being developed, tested and implemented. Corrosion prediction and monitoring have also been an area of interest in the aviation industry, and efforts have been made to predict when and how corrosion will develop.

However, this area of study is only now beginning to emerge, led by efforts from military aviation entities [6]. As this is still an experimental area, the operator attention should be directed to each aircraft or feet CPCP. The operators, or owners, should learn from the experience obtained from the aircraft over the years and, with a case-by-case, aircraft-by-aircraft or fleet-by-fleet approach, adjust the CPCPs to the operator area of operation.

The role of the CPCP in the fight against corrosion, the influence that has over numerous economic factors, but mostly, the safety level improvement that provides, were the motivation needed to integrate the project of a CPCP revision. In an operational environment, during an internship at NetJets Europe, a business jet aircraft operator, the CPCP of two aircraft fleets (Global 6000 and Falcon 2000ex Easy) were reviewed, and countermeasures studied and proposed. This work was only possible to achieve with a team effort, with critic and argumentative meetings, allowing to find the best solutions that would meet the desired results.

1.2 Objectives

The primary objective of this dissertation is to demonstrate the importance of periodic CPCP revisions, to be performed by aircraft owners and operators, in order to overcome economic and operational challenges, such as high maintenance costs and downtime, that may arise during the operation of an aircraft or fleet. Secondary objectives of this dissertation include:

- Understand the CPCP role in the fight against corrosion, from an operator's standpoint;

- Establish corrosion prone areas in specific business jet aircraft;

- Importance of root cause analyses in the identification of mechanisms and causes of corrosion damage in order to prevent its reoccurrence;

- Present proposed measures that could be implemented in other areas or other aircraft, with similar problems;

- Importance of corrosion findings databases, in the identification of recurrent corrosion problems and problematic areas, with high economic and operational impacts.

1.3 Dissertation Layout

The present thesis is structured in five chapters, with the following contents being described in each one of the chapters.

In chapter one, is made an introduction to the theme and work performed, presenting the problem in question and the dissertation objectives.

In chapter two, a literary revision is made about the corrosion process, by what factors can be influenced, and the different interaction behaviors between metals and environment. Are also presented the most common corrosion forms found in aircraft structures and components, and the principal groups of corrosive agents.

In chapter three, is presented an introduction to the Corrosion Prevention and Control Program (CPCP): the background, the importance of the program in the fight against corrosion, and how is developed and implemented into the aircraft (or fleet) maintenance program. Is also shown the role of inspections in corrosion detection, the aircraft areas most prone to corrosion and subject of more attention, the general corrosion treatment performed when corrosion is found and in what way corrosion can be prevented in in-service aircraft.

In chapter four, a description of the operator in question is made. Are also presented the methodology and metrics used in the CPCP revisions. This chapter also contains the results obtained from the fleets CPCP revisions: corrosion findings overview, corrosion economic and operational impact, root cause analyses and proposed measures for the studied cases (three for each fleet).

In the last chapter, chapter five, conclusions are presented about the work performed, and future works are established.

Chapter 2

Corrosion – Literature Review

2.1 Corrosion Theory

Most of the commonly used metals are chemically unstable (and thermodynamically stable) in their natural form [7]. To produce chemically stable metals from their natural form, either minerals or ores, it is necessary to provide a certain amount of energy. When exposed to the environment, is a matter of time until this energy is transferred again to the environment through a deterioration process, and the metals[1] revert to their original chemical and thermodynamic states, or to a similar metallic compound (such as oxide, hydroxide or sulfate), in which they were found before being refined into useful engineering materials [7, 8]. This natural deterioration phenomenon or process that results from the interaction between the metal and the environment is called corrosion, and its cycle can be seen in Figure 2.1.

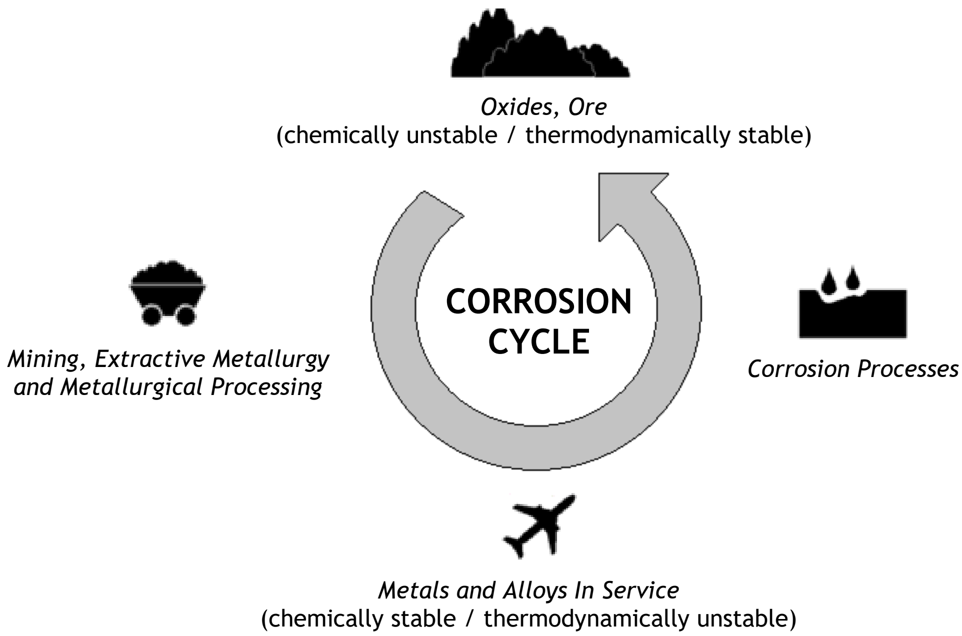


Figure 2.1: Corrosion cycle (adapted) [51].

A corrosion process can initiate on a metal due to a direct chemical or electrochemical attack.

[1] With the exception of noble metals, such as gold and platinum, that are already in their natural state.

In a direct chemical attack, the bare (unprotected) metal surface is directly exposed to a corrosive agent, with the anodic and cathodic changes co-occurring at the same location [3]. In an electrochemical attack, the anodic and cathodic changes can take place in different locations, due to the presence of a continuous liquid path (electrolyte) [3].

Nevertheless, in both corrosion attacks, the metal is converted into a metallic compound, involving two chemical changes: the metal that is attacked or oxidized undergoes an anodic change, and the oxidizing (corrosive) agent is reduced or undergoes a cathodic change [3].

2.2 Electrochemical Corrosion Cell

The electrochemical attack is responsible for most forms of corrosion on metals. Before electrochemical corrosion can occur and develop, four conditions must exist [3]:

1. Presence of an anode, or a metal that will corrode;
2. Presence of a cathode, or metal with less tendency to corrode;
3. Presence of an electrolyte (conductive liquid), in contact with the anode and cathode;
4. Electrical contact between the anode and cathode.

While is true that the elimination of any of these conditions prevents corrosion, is also true that, when all four conditions are present, corrosion develops, usually, on the metal surface, with the formation of an electrochemical corrosion cell (Figure 2.2). In this electrochemical corrosion cell take place electrochemical reactions, involving the transfer of electrons [9].

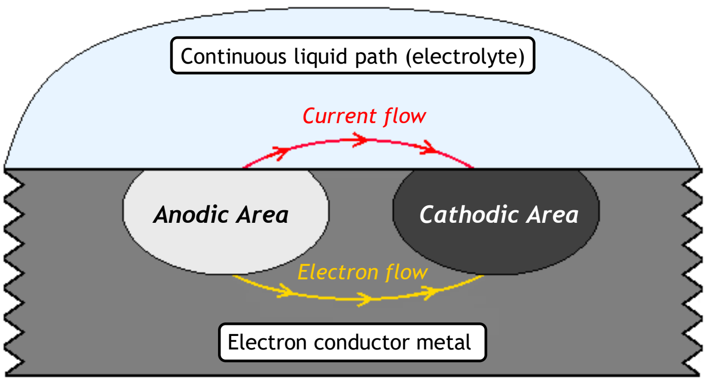


Figure 2.2: Electrochemical corrosion cell (adapted) [3].

In the electrochemical corrosion cell, the anode and cathode are connected through an ionic current path or electrolyte, and through the metal by an electric path. At the anode location, where corrosion occurs, anodic or oxidation reactions take place, with metal atoms going into the ionic current path as metal ions, observing a weight loss at this location. In the cathode area, where no corrosion or weight loss is observed, take place the cathodic or reduction reactions, with "consumption" of electrons by the cathode, originally from the anode [9]. Positively charged ions (cations) move from the anodic to the cathodic area, and negatively charged ions (anions) move from the cathodic to the anodic area. While the movement of ions is performed through the ionic current path, the movement of electrons is performed through the electronic path [9].

2.3 Environmental Interaction

According to Davis [9], when exposed to an environment, the metal can behave in one of three ways (Figure 2.3): immune, active or passive.

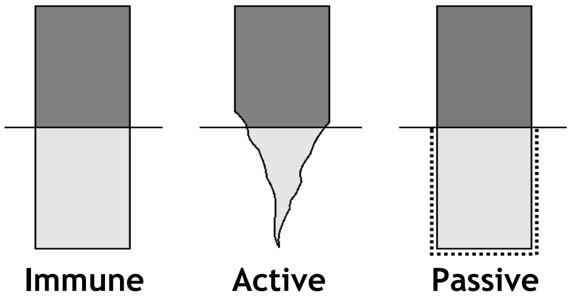


Figure 2.3: Metal behaviors when exposed to an environment (adapted) [9].

With an immune behavior, the metal is immune to that particular environment, which means that there is no reaction in the metal, the metal will not corrode, and consequently, no weight loss will be verified [9]. For a variety of corrosive environments, this behavior is only exhibited by noble metals (such as gold, silver, and platinum), but in most cases, they are not practical to use in engineering applications due to high costs and strength limitations [3, 9].

When exhibiting an active behavior, the metal corrodes and forms nonprotective corrosion products. The corrosion process will continue, since the corrosion products formed do not prevent subsequent corrosion, leading to a high weight loss [9].

If the metal corrodes, when exposed to an environment, but produces corrosion products that prevent subsequent corrosion and further weight loss, the metal exhibits a passive behavior [9]. The metal surface becomes coated with a protective film, a product of corrosion, such as an oxide or hydroxide film. These films can prevent all contact between the metal and the environment, stopping the corrosion process. However, if porous, the film will only partially prevent this contact, and corrosion can still develop, with low rates [8]. Nevertheless, if at any time the film is compromised, the metal will revert to an active behavior and the corrosion process starts again.

2.4 Factors

Most of the corrosion attacks seen on aircraft structures and components derive from the interaction between the metals and the atmosphere, such as air and its pollutants [10]. Many atmospheric factors can affect the form, speed, cause, rate, and severity of metal corrosion. In this section, it will only be described the most important atmospheric factors affecting the corrosion process: moisture, temperature, pollutants, and geographic location.

2.4.1 Moisture

The most critical factor affecting the corrosion process is the presence of moisture in a metal surface, either in the form of rain, dew, condensation or humidity. In the absence of moisture, the presence of contaminants in the metal surface does not represent a serious problem. However, when present, moisture work as an electrolyte and, if all the conditions are present, can trigger the corrosion process.

Rain can have two different corrosive impacts. Can be considered as beneficial, since it can wash away atmospheric pollutants that have settled on exposed surfaces. However, it can also be prejudicial, if trapped or collected inside structures. In addition to the fact that rainwater can be saturated with contaminants, can also form a phase layer of moisture on the metal surface, acting as an electrolyte, accelerating the corrosion process [7].

Dew formation occurs when the temperature of the metal surface is below the dew point of the atmosphere [7]. The concentration of contaminants in dew is higher than in rainwater, and if saturated with contaminants such as acid sulfates and acid chlorides, become an aggressive electrolyte for the formation of corrosion [7, 8].

When exposed to a critical level of humidity, a thin film (almost invisible) can form on a metallic surface, and as for the rainwater and dew, this thin film works as an electrolyte, which can contain high concentrations of corrosive contaminants [8].

2.4.2 Temperature

It is difficult to define the overall effect of temperature on corrosion rates since it is usually accompanied by other atmospheric conditions [7]. As temperature increases, the rate of corrosion will increase as a result of an increase in the electrochemical reactions and diffusion processes [7].

Typically, for constant humidity conditions, an increase in temperature would increase the corrosion rate. However, as temperature increases, the relative humidity levels tend to decrease, causing more rapid evaporation of the electrolyte film present on the metallic surface [7]. This process reduces the time of wetness, and consequently, the corrosion rate tends to reduce [6].

When a decrease in temperature is observed, below freezing point (0ºC), the electrolyte film present on the metallic surface can solidify or freeze [7]. As freezing occurs, the electrochemical corrosion reactions will decrease to insignificant levels, decreasing the corrosion rate [6].

2.4.3 Pollutants

The presence of specific pollutants in the atmospheric composition is one of the most important factors affecting atmospheric corrosion. The corrosive effect of a specific pollutant variety varies between different metals [7].

The two most important atmospheric pollutants that contribute to corrosion of metals are: sulfur oxides (SO_x) and nitrogen oxides (NO_x). Both are gaseous products originated from the combustion of fuels, generally from vehicle engines, being the difference that the first only is present in the combustion of fuels containing sulfur, such as diesel, gasoline or natural gas [8].

These two pollutant varieties, along with airborne aerosol particles, can react with moisture and ultraviolet radiation (UV), forming new chemicals that can be transported as aerosols [8]. However, Schweitzer [7] states that “the extent to which these pollutants will affect the corrosion rate will be influenced by the other preceding factors that also have an influence on the corrosion rate,” such as the presence of moisture.

2.4.4 Geographic Location

Geographic location is also a factor since atmospheric compositions and conditions can vary between two different locations on the globe. It is also important to refer that a metal can have excellent corrosion resistance properties in a particular area of operation, but present different properties in a different area [7].

In Annex A, it is possible to see two corrosion severity maps, relatively to the area of operation (Europe) of the business jet operator that will be analyzed in Chapter 4. The first map is from the FAA, the American aviation regulatory authority, while the second is from Cessna, an aircraft manufacturer.

In these maps, the areas are categorized as mild, moderate or severe accordingly to the respective atmospheric composition and conditions. The areas closest to the shore are categorized as either moderate or severe. In these areas is present a marine atmosphere, characterized by fine wind-swept chloride particles, that can be deposited on metal surfaces, and often present high relative humidity levels [10]. The corrosivity level of these areas is dependent on wind direction, wind speed and distance from the coast [6].

Other areas categorized as moderate or severe, usually correspond to the most developed and industrialized cities. In these areas is present an industrial atmosphere, associated with heavy industrial manufacturing facilities, which can contain concentrations of sulfur dioxide, chlorides, phosphates, and nitrates [10]. The industrial atmosphere, along with the marine atmosphere, represents the most corrosive atmospheres. These atmospheres have more impact in areas where both are present, such as industrialized cities located by the shore.

In the areas categorized as mild, is either present a rural or urban atmosphere, the least corrosive atmospheres. The rural atmosphere, the least corrosive of the two, usually does not contain chemical pollutants but does contain organic and inorganic particles [10]. The urban atmosphere, similar to the rural type in which there is little industrial activity, has pollutants derived from the burning of fossil fuels (motor vehicle and domestic fuel emissions), such as contaminants of the SO_x and NO_x variety [10].

The atmospheric corrosion severity maps tend to change over the years due to changes in atmospheric compositions in certain areas, such as an increase in industrial activity in a particular location. However, it can also change due to sporadic natural events occurring all over the world. In these natural events are included, among others, volcanic eruptions and dust winds from sandstorms.

In Europe, Iceland is one of the countries with the most active volcanoes, with three eruptions in the last ten years [11]. In 2010, the eruption of the volcano Eyjafjallajökull became the most important natural event affecting the aviation industry, with volcanic ashes[2] spreading all over Europe. In addition to the fact that volcanic ashes can damage aircraft engines, along with volcanic gas and aerosols, they are also highly corrosive. They are hard, abrasive, corrosive, conducts electricity when wet, and does not dissolve in water [12].

Sandstorms are mostly originated in desertic areas, such as the Saharan desert in Africa. Depending on wind speed and direction, mineral dust can travel to other areas as an aerosol.

[2] Fragments of rocks, minerals, and volcanic glass, ranging from 0.004 mm to 2 mm in diameter [12].

In April 2011 was observed dust, from African sandstorms, blowing across Europe, with high levels of these aerosol being recorded in Western Europe [13]. This mineral dust when deposited on structure's surfaces, especially moving surfaces, act as an abrasive medium, which can wear out any protection present in those surfaces.

2.4.5 Other Factors

Other factors can affect the corrosion process characteristics. Some of them are controllable, from a maintenance point of view, others are not. Among the controllable factors that affect the onset and spread of corrosive attack are the contact of dissimilar metals or the presence of foreign material, that adheres to metal surfaces. Such foreign material includes [3]:

- Soil and atmospheric dust
- Oil, grease, and engine exhaust residues
- Spilled battery acids and caustic cleaning solutions
- Welding and brazing flux residues
- Micro-organisms[3], such as slimes, molds, fungi and other living organisms

Relatively to the factors that can affect the corrosion process, and are not controllable from a maintenance point of view, these include [3]:

- Type of metal
- Heat treatment and grain direction (crystallization growth kinetics)
- Anodic and cathodic surface areas (in galvanic corrosion)
- Availability of oxygen
- Mechanical stress on the corroding metal
- Time of exposure to a corrosive environment

2.5 Forms of Corrosion

There are many forms of corrosion and knowing how to recognize the different forms is an advantage in understanding which mechanisms have been at work and what corrective measures to apply [8].

Corrosion, depending on the metal involved, its size and shape, atmospheric conditions, and corrosion producing agents can be categorized as either uniform or localized [3, 9]. While in

[3] can be found, for example, in fuels, and grow on damp surfaces. Once they are established, the area tends to remain damp, increasing the possibility of corrosion.

uniform corrosion, the metal corrodes at the same rate over the entire surface, in localized corrosion, only small areas are affected [9].

In this section, will be described the most common forms of corrosion found in aircraft structures and components, referenced by the FAA in reference [3].

2.5.1 General or Uniform Corrosion

General, uniform or surface corrosion (Figure 2.4), the simplest and most common form of corrosion, is often associated to a breakoff of the protective coating system, resulting in a uniform penetration over the entire exposed metal surface [9]. Appears as a general roughening or etching of the metallic surface, usually accompanied by corrosion products as a powdery deposit [3].

Caused by either a direct chemical or electrochemical attack, this form of corrosion often results from atmospheric exposure, especially in polluted industrial environments [9]. The corrosion attack results from a local corrosion cell, where an anodic and cathodic area(s) are operating on the metal surface. Eventually, the corroded area will spread on the metal surface, to other anodic and cathodic areas [3].

If the corroded area is not removed, it can lead to more severe forms of corrosion. However, some metals can resist corrosion by forming a natural passive film (thin coating), in the presence of oxygen. If the film is not broken, it prevents the corrosion process from developing. Examples of these natural films include: patina on copper, rusting of iron, tarnishes of silver, fogging of nickel, alumina on aluminum and rutile on titanium [7].

Figure 2.4: Example of general or uniform corrosion [3].

2.5.2 Localized Corrosion

Pitting Corrosion. Is one of the most common, destructive and intense forms of corrosion. Associated with the breakdown of protective films on the metal surface, occurs when one area of metal becomes anodic in relation to the rest of the surface or when highly localized changes in corrodent cause a rapidly localized attack [9]. It is first noticeable as a white or gray powdery deposit, similar to dust, but when the deposit is cleaned away, tiny holes or pits can be seen in the surface (Figure 2.5 - A) [3]. Causing failure by perforation, with only a small weight loss on the metal, the pits can be isolated from each other on the surface or close together [9]. However, the rate of penetration decreases if the number of pits increases close to each other, since adjacent pits have to share the available adjacent cathodic area, that controls the corrosion flow current [7]. It is difficult to predict and design against, and since the pits may remain covered with corrosion products, it is difficult to detect during inspection [7]. Fatigue, stress corrosion cracking (SCC), and intergranular corrosion can initiate at the base of corrosion pits [6, 8].

Crevice Corrosion. Also known as concentration cell corrosion, formed by metal-to-metal or nonmetal-to-metal contact. Tends to occur in crevices or narrow openings or spaces, such as under gaskets, washers, insulation material, fastener heads, disbonded coatings, clamps or lap joints, where a liquid (electrolyte) can be trapped [6, 7]. Results from a concentration cell formed between the electrolyte inside the crevice, which is poor in oxygen, and the electrolyte outside the crevice, with high concentrations of oxygen, creating a differential aeration cell [9]. The material inside the crevice acts as the anode, and the material outside the crevice acts as the cathode. The electrolyte is stagnant inside the crevice since the crevice is usually large enough for the entrapment of the electrolyte, but not enough to permit the flow of the electrolyte [7]. Usually taking the form of pitting or etched spots, this form of corrosion progresses very quickly after the attack begins inside the crevice [7, 8].

Filiform Corrosion. Is a particular form of crevice (oxygen corrosion cell) that occurs on metal surfaces containing an organic or metallic coating system. Filiform corrosion usually starts at small defects or breaks in the coating system and is recognized by its characteristic filaments or worm-like trace (Figure 2.5 - B) of corrosion products beneath the coating [3]. Corrosion occurs, in most of the cases, when the relative humidity of the air is between 65–90 percent, and the surface is slightly acidic [3, 9]. However, to sustain the corrosion process, oxygen or air and water are needed. Corrosion is active at the head of the filament, while the trail is mainly inactive [6]. This corrosion usually attacks steel, zinc, aluminum or magnesium surfaces, with the filament growth rate varying widely, with rates as low as 0,01 mm/day and as high as 0,85 mm/day [8, 9]. Several factors determine the development of this form of corrosion, such as preparation of the metal surface for coating, surface cleanliness, coating flexibility, thickness, and adherence to the metal surface [7].

Exfoliation Corrosion. An advanced form of intergranular corrosion, shows itself by lifting the surface grains of a metal (Figure 2.5 – C), by the force of expanding corrosion products occurring at the grain boundaries just below the surface [3]. Alloys that have a microstructure of elongated flattened grains, such as those that have been extruded, are very susceptible to exfoliation [6]. Certain alloys, such as the aluminum alloys, are also prone to this form of corrosion, especially in marine and industrial environments [9].

Galvanic Corrosion. Also called dissimilar metal corrosion, occurs when two dissimilar metals, with a common electrical path, are coupled in a corrosive electrolyte (Figure 2.5 - D). The metals are electrically active and have a specific electrical potential, which characterizes each metal corrosion resistance in a given environment [3]. The greater the difference in potential, the faster the corrosion occurs [3]. The less noble metal, with more negative electrical potential, becomes the anode and will corrode, while the more noble metal, with more positive electrical potential, becomes the cathode in the corrosion cell [8]. A galvanic series, that can be observed in Annex B, provides details of the direction of current flow between the two metals, and which metal will corrode when all the conditions are present [7]. The rate of galvanic corrosion also depends on the size of the dissimilar metals in contact. If the cathode area is greater than the anode area, corrosion is rapid and severe; if the cathode area is smaller than the anode area, corrosion is slow and superficial [3].

Stress Corrosion Cracking (SCC). This form of corrosion involves a mechanical (tensile stress) and chemical (corrosion) process leading to the cracking of some alloys (Figure 2.5 - E), difficult to detect until extensive corrosion has developed [7]. The two processes need to act at the same time for SCC to occur. Corrosion alone will not produce SCC; however, it is not necessary high concentrations of corrodent to cause it [7]. The stress may be caused by internal loading, trapped during manufacturing processes, or by external loading, introduced in part of the structure by riveting, welding, bolting, clamping, press fit, etc. [3]. Pitting and fatigue corrosion often lead to SCC initiation [7, 8].

Intergranular Corrosion. The metals and alloys microstructure is made up of grains, separated by boundaries. Intergranular corrosion (Figure 2.5 - F) is a localized attack along the grain boundaries or adjacent areas, while most of the grain main body remains unaffected, resulting in the loss of strength and ductility [6, 7]. This type of corrosion commonly results from a lack of uniformity in the alloy or metal microstructure, caused by changes in the microstructure during the metal or alloy thermal processing, such as welding, stress relief, and other heat treatments [3, 7]. Aluminum alloys and some stainless steels are particularly susceptible to this form of corrosion [3].

Fretting Corrosion. Is a particularly damaging form of corrosive attack that occurs when two mating surfaces, generally at rest with respect to one another, are subject to repeated relative surface motion, such as vibration [3]. The protective film on the metal surfaces is removed by the rubbing action and exposes the metal surface to the corrosive action of the environment [8]. This form of corrosion is characterized by pitting of the surfaces and the generation of considerable quantities of oxide debris (Figure 2.5 - G). Since the restricted movements of the two surfaces prevent the debris from escaping very easily, an extremely localized abrasion occurs [3]. Lubrication of the two surfaces may help prevent this form of corrosion [9].

Fatigue Corrosion. This form of corrosion usually involves cyclic stress and a corrosive environment. Metals may withstand cyclic stress for an infinite number of cycles, as long as the stress is below the endurance limit of the metal. When the limit is reached and exceeded, the metal eventually cracks and fails from metal fatigue [3]. However, when the part or structure subjected to cyclic stress is also exposed to a corrosive environment, the number of cycles required to cause failure at a given stress may be reduced many times [9]. Thus, failure occurs at stress levels that can be dangerously low depending on the number of cycles assigned to the life-limited part [3]. Fatigue corrosion failure occurs in two stages: 1) the combined action of corrosion and cyclic stress damages the metal by pitting and crack formations to such a degree that fracture by cyclic stress occurs (even if the corrosive environment is no longer affecting the area), 2) failure proceeds by propagation of the crack (often from a corrosion pit or pits) [3].

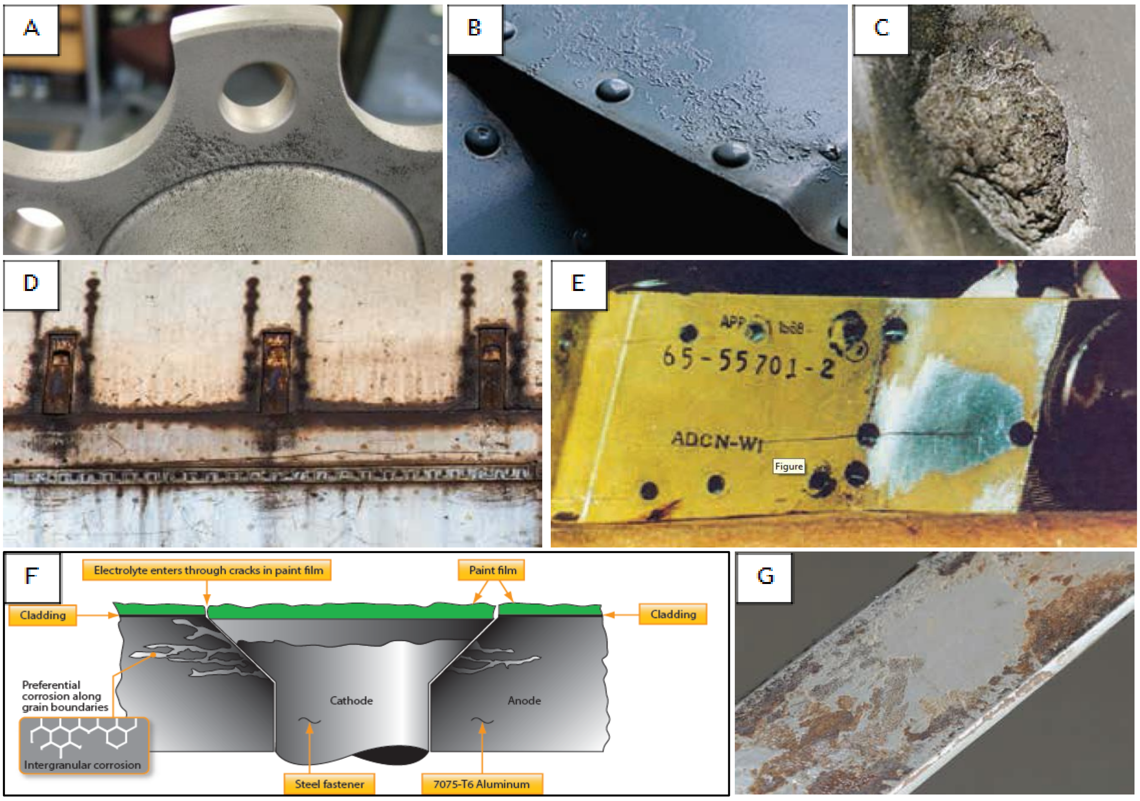


Figure 2.5: Localized forms of aircraft corrosion (Legend: A – Pitting Corrosion; B – Filiform Corrosion; C - Exfoliation Corrosion; D - Galvanic Corrosion; E - Stress Corrosion Cracking; F - Intergranular Corrosion; G - Fretting Corrosion) (adapted) [3, 51].

2.6 Common Corrosive Agents

Substances that cause corrosion of metals are called corrosive agents. In Table 2.1, five groups of the most common corrosive agents are described.

Table 2.1: Group description of corrosive agents (adapted) [3].

Group	Description
Acids	The most destructive are sulfuric acid (battery acid), halogen acids (hydrochloric, hydrofluoric, and hydrobromic), nitrous oxide compounds, and organic acids found in the wastes of humans and animals.
Alkalis	Not as corrosive as acids. Aluminum and magnesium alloys are exceedingly prone to corrosive attack by many alkaline solutions unless the solutions contain a corrosion inhibitor. Substances particularly corrosive to aluminum are washing soda, potash (wood ashes), and lime (cement dust).
Salts	Most saline solutions are good electrolytes and can promote corrosive attack. Aluminum alloys, magnesium alloys, and some steels are extremely vulnerable.
Atmosphere	Corrosion often results from the direct action of atmospheric oxygen and moisture on metal, and the presence of additional moisture often accelerates corrosive attack, particularly on ferrous alloys. However, the atmosphere may also contain other corrosive gases and contaminants, particularly industrial and marine salt spray.
Water	Depends on the type and quantity of dissolved mineral and organic impurities and dissolved gases (particularly oxygen) in the water. One characteristic of water that determines its corrosiveness is the conductivity or ability to act as an electrolyte and conduct current. Physical factors, such as water temperature and velocity, also have a direct bearing on its corrosiveness.

The most common corrosive agents are acids, alkalis, and salts. The atmosphere and water, the two most common media for these agents, may also act as corrosive agents [3]. Most of the corrosion attacks in aircraft are originated by the interaction between the materials and the environment, such as atmosphere and rainwater, which can contain pollutants and marine salt particles. Another common source of corrosive agents on aircraft are the batteries, usually containing acids. Even though the recent use in aircrafts of sealed lead-acid and nickel-cadmium batteries have been less of a problem, those who have batteries containing electrolytes, sulfuric acid or potassium hydroxide, are often very problematic in aircraft batteries compartments, since their leakage usually leads to a direct chemical corrosion attack on bare (unprotected) metal surfaces.

Chapter 3

Corrosion Prevention and Control Program (CPCP)

3.1 CPCP: definitions and regulations

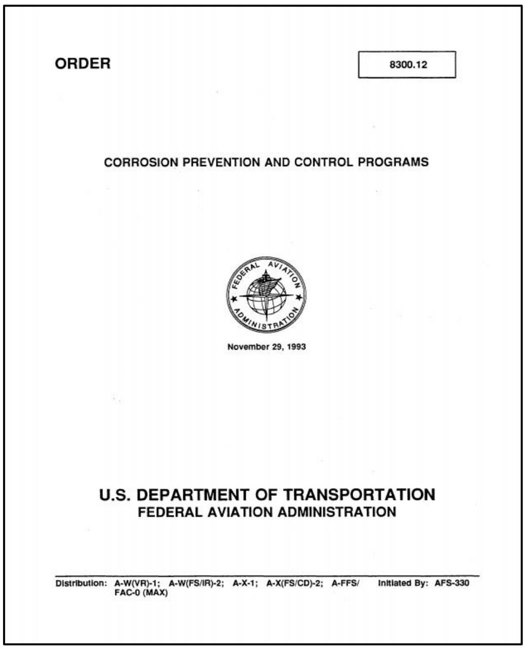
The investigation of the Aloha Airlines Flight 243 accident, performed by the National Transportation Safety Board (NTSB) in 1988, showed that, at the time, corrosion was not considered a real and severe problem. While a program for control and prevention of corrosion was not established, the signs of on-going corrosion damage were declared as normal operating conditions, and the respective corrective actions were often deferred without any basis for deferral [5]. Due to the inexistence of a program to control and prevent corrosion in aircraft, the Federal Aviation Administration (FAA) developed a model for a comprehensive CPCP, that would be included in each operator Approved Maintenance Program (AMP). In November 1993, the FAA published the document FAA Order 8300.12 (Figure 3.1) to guide operators in the development of a CPCP [5].

The CPCP is a systematic approach to maintain the aircraft resistance to corrosion, as a result of a chemical or environmental interaction [14]. In order words, the CPCP aims to limit the material loss due to corrosion to a level necessary to maintain airworthiness, achieved by defined inspections, repair, and preventive tasks.

3.1.1 Corrosion Levels

According to FAA Order 8300.12, the corrosion level is a “means of determining the effectiveness of a CPCP relative to a given corrosion finding in terms of the severity of corrosion and the potential consequences to continuing airworthiness in the operator's fleet.” The Baseline Programs recognize three levels of corrosion that are used to assess CPCP effectiveness. According to Giles et al. [15], the European Aviation Safety Agency (EASA) defines the three levels as follow:

- **Corrosion Level 1**:
    (a) Corrosion occurring between successive inspection tasks that is local, and can be reworked or blended out with allowable limits; or



ORDER 8300.12

CORROSION PREVENTION AND CONTROL PROGRAMS

FEDERAL AVIATION ADMINISTRATION

November 29, 1993

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Distribution: A-W(VR)-1; A-W(FS/IR)-2; A-X-1; A-X(FS/CD)-2; A-FFS/ FAC-0 (MAX) Initiated By: AFS-330

Figure 3.1: FAA Order 8300.12 cover (Corrosion Prevention and Control Programs) [5].

(b) Corrosion damage that is local and exceeds the allowable limit but can be attributed to an event not typical of operator's usage of other aircraft in the same fleet (e.g., mercury spill); or

(c) Operator experience has demonstrated only light corrosion between each successive corrosion inspection task, and the latest corrosion inspection task results in rework or blend-out that exceeds the allowable limit.

- **Corrosion Level 2**[1]:
    (a) Corrosion occurring between any two successive corrosion inspection tasks that require a single rework or blend-out that exceeds the allowable limit; or
    (b) Corrosion occurring between successive inspections that is widespread and requires a single blend-out approaching allowable rework limits (i.e., it is not light corrosion as provided for in the Level 1 definition).

- **Corrosion Level 3**[2]:
    (a) Corrosion occurring during the first or subsequent accomplishments of a corrosion inspection task that the operator determines to be an urgent airworthiness concern.

[1] A finding of Level 2 corrosion requires repair, reinforcement, or complete or partial replacement of the applicable structure [15].
[2] If Level 3 corrosion is determined at the implementation threshold or any repeat inspection, and any corrosion that is more than the maximum acceptable should be reported [15].

The CPCP is expected to allow control of the corrosion on the aircraft to Corrosion Level 1 or better. If, at any inspection, corrosion is found to exceed Level 1, the corrosion control program for the affected area must be reviewed by the operator with the objective to ensure Corrosion Level 1 or better [5].

3.1.2 CPCP Development and Implementation

The CPCP is a specific program for inspection, treatment, and repair of corrosion on aircraft, and should be implemented and maintained by the operator. The operator has two options [5]:

(1) Develop a CPCP from scratch, adjusted to their operations, based on the aircraft manufacturer baseline program, or
(2) Adopt the aircraft manufacturer program in total.

Before the Maintenance Steering Group-3[3] (MSG-3), the CPCP was mandated by Airworthiness Directives. Under MSG-3, the CPCP has been integrated into the operator AMP and included as part of the structure's maintenance program. This integration into the maintenance program significantly eliminates duplicative tasks [16].

3.2 Corrosion-related Aviation Events

More than any economic impact, human life is priceless, and corrosion has played its part in numerous aircraft accidents and incidents. The most critical event in the history of aviation, which would have a significant impact on corrosion awareness, was the Aloha Airlines Flight 243, described below. Other events are also presented, where aircraft structural failures due to corrosion, led to the loss of human lives or were put at risk.

3.2.1 Aloha Airlines Flight 243

On 28 April 1988, the Boeing 737-297 from Aloha Airlines, flight 243, departed from Hilo Int'l Airport, Hawaii, USA, en route to Honolulu Int'l Airport, Hawaii, US, when a segment on the left side of the upper fuselage (roof), ruptured from the front of the aircraft (Figure 3.2), forcing an emergency landing on Kahului Airport, Hawaii, US [17].

[3] The MSG-3 is a document published in 1980, developed by the Airlines For America (A4A) (formerly ATA). It aims to present a methodology to be used for developing scheduled maintenance tasks and intervals, which will be acceptable to the regulatory authorities, the operators and the manufacturers. The objective of this concept is to recognize the inherent reliability of aircraft systems and components, avoid unnecessary maintenance tasks and achieve increased efficiency [45].

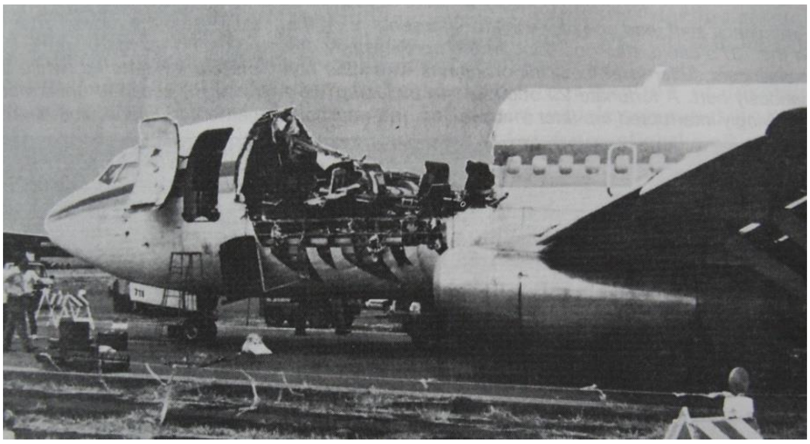


Figure 3.2: Aloha Airlines Boeing 737-297 without a portion of the fuselage structure [17].

This event “initiated with the structural separation of the pressurized fuselage skin. As a result of this separation, an explosive decompression occurred, and a large portion of the airplane cabin structure comprising the upper portion of section 43 was lost” [17].

The pilots were able to land the aircraft safely, on the Kahului Airport, allowing 94 people to survive (89 passengers and 5 crew members), which 65 of them were reported injured. The only fatality was the flight attendant who was standing in the area where the fuselage skin ruptured, being ejected out of the cabin due to the decompression effect [17].

After the investigation, the NTSB accident report showed that the probable cause of this accident was the failure of Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue cracking which led to the failure of a lap joint and consequently separation of the fuselage upper lobe [17]. Fatigue cracking was not anticipated to be a problem, as long the overlapping fuselage panels, connected by the lap joints, remained strongly bonded together [6]. Early production difficulties in the cold bond of lap joints in this aircraft, resulting in low bond durability, originated in a buildup of voluminous corrosion products between the two panels, inside the lap joints [6, 17]. This led to pillowing (Figure 3.3), with the overlapping surfaces being separated, and increasing the stress level near critical fastener holes [6].

The investigation showed some factors of concern in the Aloha Airlines aircraft maintenance program [17, 18]:

- High accumulation of flight cycles between structural inspections;
- Extended intervals between inspections, allowing the effects of lap joint disbond, corrosion, and fatigue to accumulate;

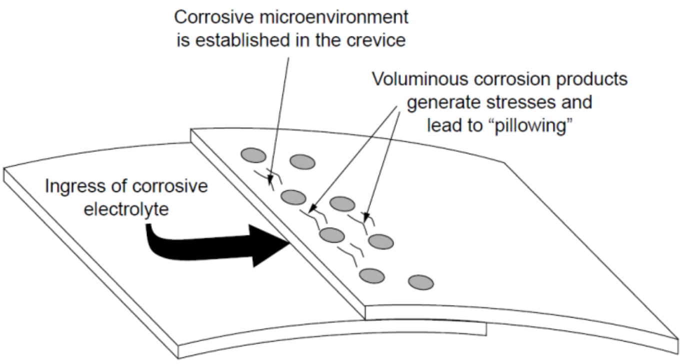


Figure 3.3: Pillowing of lap splices [6].

- The manner in which a highly segmented structural inspection program was implemented;
- Corrosion Control Program not established by the operator, with every corrosion finding, or its repairs not being duly followed and controlled.
- Operator AMP not adjusted to a maritime operating environment;
- Inexistent operator Engineering capabilities, with the technical documentation from manufacturers or airworthiness authorities not being adequately analyzed by an Engineering department, which led to failures in accomplishing the Airworthiness Directive (AD) 87-21-08.

The report also showed failures from the FAA to evaluate properly all the concerning factors shown by the Aloha Airlines maintenance program and to require the AD 87-21-08 inspection of all lap joints, proposed by a Boeing Alert Service Bulletin [17].

3.2.2 Other Incidents and Accidents

Other relevant aircraft incidents and accidents are presented in Table 3.1, where system failures, with ineffective or inexistent CPCP, were, directly or indirectly, the cause of those events.

Table 3.1: Corrosion-related aircraft accidents and incidents.

OPERATOR	**EVENT INFORMATION**	
British European Airways	**Date**	2 October 1971
	Aircraft	Vickers Vanguard 951
	Flight No.	706
	Phase	En route
	Failure	Major rupture in the rear pressure bulkhead, which caused the tail planes to become pressurized. The resultant loss of the major portion of both horizontal tail surfaces caused

Table 3.1: Corrosion-related aircraft accidents and incidents (Continued).

OPERATOR	EVENT INFORMATION	
		the aircraft to enter a steep dive from which it was not possible to recover [19].
	Factor	Severe corrosion present at the joint between the fuselage skin and the rear pressure bulkhead had been present unseen for an unknown period before the accident. Also, the relatively long intervals for the visual inspection of the bulkhead, in combination with the use of an inappropriate corrosion inspection technique (radiographic), allowed the corrosion to develop in that area undetected, which led to the structural failure [19].
Rich International Airways	**Date**	28 February 1994
	Aircraft	Lockheed L-1011 TriStar 1
	Flight No.	303
	Phase	Takeoff
	Failure	Failure of the sixth stage disc on the intermediate compressor stage 6/7th rotor shaft assembly in the number three engine, due to corrosion pitting and fatigue cracking of the failed disc [20].
	Factor	Failure of the airline company to follow provisions of the service bulletin [20].
Atlantic Southeast Airlines	**Date**	21 August 1995
	Aircraft	Embraer EMB-120ER Brasília
	Flight No.	529
	Phase	En route
	Failure	Fatigue fracture and separation of a propeller blade resulting in distortion of the left engine nacelle, causing excessive drag, loss of wing lift, and reduced directional control of the airplane. The fracture was caused by a fatigue crack from multiple corrosion pits [21].
	Factor	Corrosion undetected by Hamilton Standard because of inadequate and ineffective corporate inspection and repair techniques, training, documentation, and communication [21].
Icelandair	**Date**	28 June 2001
	Aircraft	Boeing 757-208
	Flight No.	-
	Phase	Boarding
	Failure	The boarding of the aircraft was almost completed when right-hand main landing gear's truck beam failed. As the right-hand truck beam failed, the aircraft's right side rested on the shock strut instead on the wheels. The

Table 3.1: Corrosion-related aircraft accidents and incidents (Continued).

OPERATOR	EVENT INFORMATION	
		failure was caused by a pre-existing crack in the beam, which in turn was caused by hydrogen induced stress corrosion, starting from inside the beam [22].
	Factor	Overhaul procedures of the truck beams were improper and did not follow the Component Maintenance Manual (CMM). The improper overhaul resulted in inadequate corrosion protection of the inner diameter of the truck beams, which lead to the occurrence [22].
Manx2	**Date**	8 March 2012
	Aircraft	British Aerospace 3102 Jetstream 31
	Flight No.	309
	Phase	Landing
	Failure	Failure of the landing gear due to a crack emanating from the top edge of the forward yoke pintle. The crack resulted from SCC and massive corrosion deposits [23].
	Factor	The amount of corrosion in the crack and on the steel spigots suggests that it was present during the last visual inspection, performed 11 days before the flight, and may have been present during the last eddy current inspection performed ten months before the flight [23].
FedEx Express	**Date**	28 October 2016
	Aircraft	McDonnell Douglas MD 10-10F
	Flight No.	FX910
	Phase	Landing
	Failure	The left main landing gear collapsed after landing on the runway. The failure of the left main landing gear fill valve due to fatigue cracking that initiated at a corrosion pit, that developed in the absence of a required protective cadmium coating [24].
	Factor	Operator overhaul limit exceeded that recommended by the aircraft manufacturer without sufficient data and analysis to ensure crack detection before it progressed to failure [24].

3.3 Inspection

Nowadays, more attention is given to early detection of corrosion damages, since this practice often results in improved safety and lower maintenance costs. Corrosion can be detected through regular scheduled corrosion inspections, essential to determine the condition of a structure or component and perform the respective corrective actions before failures occur. It is also important to evaluate the efficiency of the implemented CPCP. Corrosion inspections are usually performed following the steps [3]:

1. Thorough cleaning of the area to be inspected;
2. General visual inspection of the area using a flashlight, inspection mirror, and magnifying glass;
3. If damages or suspected damages are found during the general inspection, a detailed inspection should be performed for a better evaluation of the problem.

If a detailed inspection is to be performed, one or more nondestructive inspection (NDI) methods, can be used for a more efficient corrosion damage detection and evaluation [3]. For example, the acoustic emission and ultrasonic inspections methods, when used together can, in principle, allow a more efficient inspection of an entire structure, in terms of damage depth and length [6]. Nevertheless, the choice of the right NDI method to use should rely on the accuracy to inspect a particular area, the material properties, or the type of defect [6].

Is also important to refer that the NDI methods, that will be described, present limitations and only should be performed by qualified and certified NDI personnel. To obtain reliable results, some NDI methods (eddy current and ultrasonic) also require properly calibrated per-use equipment with a reference standard [25].

3.3.1 Visual Inspection

Visual inspection is the most used, quick, economical and effective method for detection and evaluation of corrosion [3, 6]. This method uses the sense of sight (eyes) to search for corrosion signs, by looking directly at an aircraft surface [3].

To perform this type of inspection, the surface must be cleaned and accessible to the naked eye or optical tool. Can only be used to inspect corrosion damages at the surface of a structure or component. However, some internal corrosion attacks produce indications, such as blistering or pillowing, visible at the material surface [6]. If given the proper access to inspect a specific area, the inspector can visualize some types of corrosion damage on the surface of the material, such as surface corrosion, exfoliation, pitting and intergranular corrosion [6].

Tools such as flashlights, mirrors, borescopes, optical micrometers, depth gauges, and fiber optics can be used to assist the inspection [25].

3.3.2 Liquid Dye Penetrant

The liquid dye penetrant is used to detect faults that have a narrow opening in the material surface, such as large stress-corrosion or corrosion fatigue cracks on nonporous ferrous or nonferrous metals [3, 6]. This method has relatively low costs of utilization and is highly accurate if performed correctly [6].

Can be used in complex shape structures or components, to detect open-to-the-surface cracks, surface anomalies and pitting. However, cleaning of the surface should be performed before the application of the liquid [6].

The dye will enter cracks, fissures, or other small openings by capillary action when applied to a clean metallic surface. After absorption by any of this surface discontinuities, the excess dye is removed, and a developer substance is applied to the surface [25]. The magnitude of the fault is indicated by the quantity and rate of dye on the surface after the developer application [25].

3.3.3 Magnetic Particle Inspection

The magnetic particle inspection is used to detect cracks or defects on or near the surface of ferromagnetic metals, or metals that sustain a magnetic field [3, 6]. Like the liquid dye penetrant inspection method, this method has relatively low costs of usage and can be used to inspect complex shapes [6].

A portion of the metal is magnetized and coated with finely divided magnetic particles, either in liquid suspension or dry. Surface faults will create discontinuities in the magnetic field and cause the particles to congregate on or above these faults, showing the damages location [25].

3.3.4 Eddy Current Inspection

The eddy current inspection method detects thinning due to corrosion and cracks in multilayered structures [3]. With properly calibrated instruments, this method presents very accurate results. However, it requires that the material to be inspected is electrically conductive and capable of uniform contact with an eddy current probe, since it is sensitive to changes in geometry or shape [6].

Low-frequency eddy current (LFEC) testing can estimate corrosion in the underlying structure because the currents will penetrate through into the second layer of material with sufficient sensitivity for approximate results [25]. High-frequency eddy current (HFEC) testing is most appropriate for detection of cracks which penetrate the surface of the structure [25].

3.3.5 X-Ray Inspection

X-Ray Inspection is used to detect surface and subsurface material discontinuities [6]. Moderate to severe corrosion or cracks can be detected using X-ray inspection [3].

This technique uses special films or electronic devices, to register the passage of electromagnetic waves of very short wavelength, X-rays, that go through the material [3, 6]. The X-rays penetrate the material and are absorbed, depending on the thickness or the density of the structure or component material being examined. Variations in the material can be detected by the recorded differences in absorption of the transmitted waves [6].

3.3.6 Ultrasonic Inspection

The ultrasonic inspection provides a sensitive detection capability for corrosion damage, when access is available to a surface with a continuous bulk of material exposed to the corrosion [3]. However, ultrasonic digital thickness gauges are not reliable for determining moderate or severe damage prior to removing corrosion [25].

A sound wave is generated into the part being examined. The signal reflects and is returned and analyzed. The time needed for the signal to return and the amount and shape of the signal determines the extent of the damage. The material being analyzed must support the propagation of acoustic energy and have a geometric configuration that allows the introduction and detection of acoustic energy in the reflection, transmission, or scattered energy configurations [6].

3.3.7 Acoustic Emission

The acoustic emission inspection uses heat-generated emissions to detect corrosion and moisture in adhesive-bonded metal honeycomb structures [3]. It can be used over relatively large areas of structures; however, it can only be used to detect defects that are actively growing at the time of the inspection [6].

3.4 Corrosion Prone Areas

Through experience, it is known that are certain areas (usually common to all aircraft) that, due to a combination of factors, are prone to corrosion [3]. These areas should be subject of special attention, meaning that they should be inspected, cleaned, and treated more frequently than less corrosion prone areas. Corrosion prone areas include [3]:

- *Exhaust trail areas* – both jet and reciprocating engine exhaust deposits are very corrosive and give particular trouble where gaps, seams, hinges, and fairings are located downstream from the exhaust pipes or nozzles. In remote areas, such as the empennage surfaces, exhaust deposit can buildup, and may not be noticed until corrosive damage has begun.

- *Battery compartments and battery vent openings* – fumes from overheated electrolyte or leakage of batteries containing electrolytes, sulfuric acid, or potassium hydroxide can spread to adjacent holes, where corrosion will develop, in a short time interval, in bare metal (unprotected) surfaces.

- *Lavatories, buffets, and Galleys* – adjacent to these areas, contaminants (spilled food, waste products) may collect. Even though some contaminants are not corrosive in themselves, they can attract and retain moisture, working as an electrolyte, which in turn can help start the corrosion process.

- *Wheel well and landing gear* – this area probably receives more punishment due to mud, water, salt, gravel, and other flying debris, which can work as corrosive agents or abrasive mediums.

- *Water Entrapment Areas* - due to design specifications, all the areas where water may collect require that the aircraft have drains installed, since water works as an electrolyte, water entrapment could lead to corrosion. Since drain holes can be blocked by accumulated debris, grease or sealants, becoming ineffective, they also represent a trouble area.

- *Engine frontal areas and cooling air vents* - these areas are being constantly abraded with airborne dirt and dust, bits of gravel from runways, and rain erosion, leading to the removal of the protective finish.

- *Wing flap and spoiler recesses* - dirt and water may collect unnoticed in the flap and spoiler recesses because they are normally retracted.

- External skin areas - external aircraft surfaces are visible and accessible for inspection and maintenance. Corrosion of metal skins joined by spot welding is the result of the entrance and entrapment of corrosive agents between the layers of metal. This type of corrosion is evidenced by corrosion products appearing at the crevices where the corrosive agents enter. More advanced corrosive attack causes skin buckling and eventual spot weld fracture.

- *Electronic and electrical compartments* – in these areas are located components, such as circuit breakers, contact points, and switches, which are extremely sensitive to moisture and corrosive attack. When these compartments are cooled by ram air or compressor bleed air, they are subjected to the same conditions common to engine and accessory cooling vents and engine frontal areas, however, with a lower degree of exposure.

3.5 Corrective Actions

Nowadays, corrosion damages are no longer tolerated on aircraft structures or components, since these damages can result in personal injuries or fatalities. When corrosion is found during the inspection, in an aircraft structure or a component, however slight, is damage and needs to be repaired [3].

The repair of the corrosion damage usually involves cleaning and stripping of the corroded area, removing as much of the corrosion and corrosion products as practicable, neutralizing any residual materials remaining in pits and crevices. After the repair, measurements are taken for evaluation. If the damage is within negligible[4] limits, protective surface films are restored, and temporary or permanent coatings or paint finishes are applied [3, 26].

If the damage is not within negligible limits and the relative costs and availability are low, the damaged area is repaired by patching or by insertion, following the applicable Structural Repair Manual (SRM). When a new component is more affordable, compared to the relative costs of the patch or insertion repair, then the affected component is removed from the aircraft and replaced by a new one. This maintenance philosophy is called “find and fix,” demonstrated in the flowchart of Figure 3.4 [26].

[4] Negligible damage, generally, is corrosion that has scarred or eaten away the surface protective coats and begun to etch the metal [3].

If the corrosion damage exceeds the damage limits, set by the aircraft manufacturer in the SRM, to the extent that repair is not possible, the component or structure needs to be replaced, regardless of the costs associated with the replacement [3].

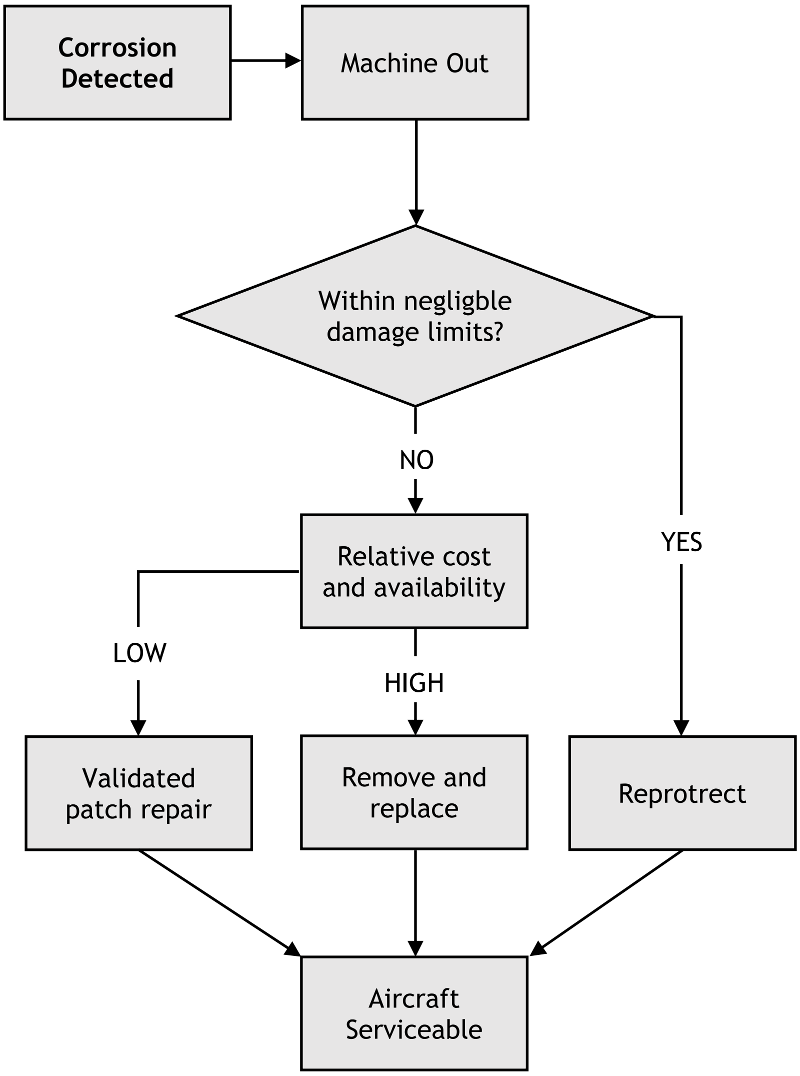


Figure 3.4: "Find & Fix" philosophy (adapted) [26].

3.5.1 Surface Cleaning and Paint Removal

The removal of corrosion includes removal of surface finishes covering the attacked or suspected corroded area. This preliminary cleaning operation is an aid in determining the extent of spread of corrosion, since the stripping operation is held to the minimum consistent with full exposure of the corrosion damage [3]. The selection of the products to be used in cleaning depends on the nature of the material to be removed.

When using paint remover, attention should be given to the protection of some materials, such as synthetic rubber surfaces, including aircraft tires, fabric, and acrylics, against possible contact with the paint remover [3]. Particular attention should also be given when using paint remover around gas or watertight seam sealants since the stripper tends to soften and destroy the integrity of these sealants [3].

3.5.2 Corrosion Removal

Several standard methods are available for corrosion removal, being either mechanical or chemical. Mechanical methods include hand sanding using an abrasive mat, abrasive paper, or metal wool, and powered mechanical sanding, grinding, and buffing, using an abrasive mat, grinding wheels, sanding discs, and abrasive rubber mats [3].

3.5.3 Blending

After the corrosion and corrosion products are removed from the component or structure, all depressions need to be faired or blended with the surrounding surface [25].

In critical and highly stressed areas, all pits remaining after the removal of corrosion products must be blended out to prevent stress risers, that can potentially lead to stress corrosion cracking [3]. In areas having closely-spaced, multiple pits, intervening material must be removed to minimize surface irregularity or waviness [25]. All corrosion products must be removed during blending to prevent reoccurrence of corrosion.

3.6 Preventive Maintenance

To ensure that the aircraft maintains the corrosion resistance properties, through the entire operational life, exists a shared responsibility by two entities: aircraft manufacturer and operator.

The aircraft manufacturer should take into account, in the design phase, the aircraft corrosion resistance properties, eliminating many corrosion problems, and reducing time and costs associated with corrosion maintenance and repair [9]. This is achieved with: selection of more corrosion resistance metals, application of coatings, corrosion inhibitor compounds and other protections with excellent corrosion resistance properties, addition of drainage systems were water is expected to be trapped, avoid contact between dissimilar metals by insulating the two metals from each other (such as use of plastic washers between fasteners, or bolts, and the structure surface), etc.

From the aircraft operator, is expected the maintenance of the corrosion prevention systems implemented by the aircraft manufacturer, or addition of new and more effective systems, in in-service aircraft. This is possible with preventive maintenance, performed at regular intervals, often resulting in reduced failure rates [6].

The inspections, described in section 3.3, constitute a preventive maintenance task. Preventive maintenance can also be accomplished by correctly performing other specific maintenance tasks, such as [3]:

- Adequate cleaning
- Thorough periodic lubrication
- Detailed inspection for failure of protective systems
- Prompt treatment of corrosion and touch up of damaged paint areas
- Accurate record keeping and reporting of material or design deficiencies to the aircraft manufacturer
- Use of appropriate materials, equipment, technical publications, and adequately-training personnel
- Maintenance of the basic finish systems
- Keeping drain holes free of obstructions
- Daily draining of fuel cell sumps
- Daily cleaning of exposed critical areas
- Sealing of aircraft against water during foul weather and proper ventilation on warm, sunny days
- Replacing deteriorated or damaged gaskets and sealants to avoid water intrusion and/or entrapment
- Maximum use of protective covers on parked aircraft

If corrosion prevention of the aircraft is poor or inexistent, the amount of maintenance needed to repair accumulated corrosion damage and bring the aircraft back up to standard is usually quite high [3]. In this dissertation, special attention and awareness are given to preventive maintenance that should be performed by the operator.

Chapter 4

NetJets Europe CPCP Revisions

4.1 NetJets Europe: Introduction

NetJets Europe (NetJets Transportes Aéreos, S.A.), the largest business aviation company in Europe, partially owned subsidiary of NetJets Inc. (owned by Berkshire Hathaway), provides air transportation services in Europe.

Its offices are spread over Europe, with sales and marketing based in London, United Kingdom, while the operations headquarters are in Paço de Arcos, Lisbon, Portugal (Figure 4.1). Operates in over 5000 airports worldwide with over 43 European airports serving as gateways [27].

Figure 4.1: NetJets Europe Operations Headquarters in Paço de Arcos (street view from Google Maps).

The five different fleets owned by NetJets Europe, are categorized as one of the four types of categorization of cabin capacity [28]:

- Embraer PHENOM 300 (light cabin - up to 6 passengers)
- Cessna CITATION LATITUDE (midsize cabin - up to 7 passengers)
- Bombardier CHALLENGER 350 (super-midsize cabin - up to 9 passengers)
- Dassault FALCON 2000EX EASY (large cabin - up to 10 passengers)
- Bombardier GLOBAL 6000 (large cabin - up to 13 passengers)

4.2 Revision Methodology

In this work, the CPCP of two NetJets Europe fleets were reviewed: Global 6000 and Falcon 2000ex Easy. Nevertheless, the same seven-step methodology was used for both fleets:

1. Find what inspection blocks, and respective work orders, contained CPCP tasks (corrosion inspection tasks);

2. Search for corrosion findings, in the work orders previously selected;

3. Form a database with all the fleet corrosion findings, containing the respective information: tail, finding ata chapter[1], finding date, finding description, corrective action, maintenance costs and labor hours;

4. Analyze the data (area affected, recurrence, maintenance costs and labor hours), for a better understanding of the critical areas that needed to be further analyzed;

5. Root cause analyses of the corrosion problems showing the most significant impact, economically and operationally. Recurrence within the fleet was also considered a choosing factor;

6. Search, in aircraft manufacturer and OEM documentations (Service Bulletins[2], Recommendations, etc.), for enhancements that could improve the current state of the corrosion problem, that had not been complied with at the time of this work. For cases without improvements, search for new and enhanced corrosion prevention products in specialized aircraft corrosion companies. Changes in task procedures and task intervals could also present as potential measures;

7. Presentation of the respective measures to the Maintenance Engineering Program Technicians, Fleet Managers, Head of Engineering and Director of Maintenance & Engineering, for discussion and approval.

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[1] The Ata iSpec 2200 (formerly know as ATA 100), developed by the Technical Information and Communications Committee (TICC) in 2000, is an improved numerical technical classification of all the systems and sub systems on an aircraft, which is universally used in aircraft engineering and aircraft maintenance [46].

[2] A Service Bulletin (SB) is a document used by the aircraft manufacturers, or from components OEM, to communicate to the aircraft operators, details of a component or structural improvement [47]. If the SB is not an alert SB or a bulletin referenced in an AD, it becomes optional, and it is up to the operator to decide if the SB should be incorporated [48].

4.3 Analyse Approach

The approach used in this dissertation, to present the problems found in the CPCP revisions, is described as follow:

- Presentation of the aircraft;
- Quantification of corrosion damages;
- Comparison between aircraft of the same fleet;
- Economic and operational impact;
- Analysis of structure or components case studies, where corrosion was observed to have the most significant impact;
- Corrosion problems description;
- Countermeasures proposed.

4.3.1 Metrics

To help evaluate the efficiency of the CPCPs when dealing with corrosion, the following metrics were used: maintenance costs and labor hours. Included in maintenance costs are the costs associated with:

- Time spent in the repair and treatment of corrosion;
- Materials and parts used;
- Premature replacement of aircraft components.

In this dissertation, the corrosion economic impact is presented in terms of cost percentage, i.e., for each area or aircraft is shown the economic weight of the respective corrosion finding(s) in relation to the entire corrosion costs of the fleet. To obtain the cost percentage, or cost weight, the equation presented in 4.1 was used.

$$Cost\ Percentage_{\ area\ or\ aircraft}\ (\%) = \frac{Corrosion\ Costs_{\ area\ or\ aircraft}}{Total\ Fleet\ Corrosion\ Costs} \qquad (4.1)$$

Hours spent gaining access to equipment that has corrosion damage and spent in the repairing and treatment of the corrosion damage were considered as labor hours. In Annex C are presented a list of activities usually performed when inspecting and repairing corrosion damages, accounted as labor hours.

4.4 Global 6000

The Global 6000 (Figure 4.2) is an aircraft manufactured by Bombardier, with a low wing (with winglets), T-tail and a tricycle landing gear configuration. The aircraft present the following specifications and performance [29]:

Crew: up to 4
Passengers: up to 13
Height: 25 ft 6 in
Wingspan: 94 ft 0 in
Length: 99 ft 5 in
Maximum Range[3]**:** 6000 nm
Maximum Fuel Weight: 45050 lb
Maximum Payload: 5770 lb
Maximum Takeoff Weight: 99500 lb
Maximum Operating Altitude: 51000 ft

Figure 4.2: NetJets Europe Global 6000 aircraft (CS-GLE) [53].

Engine: BR710A2-20
Thrust: 14750 lbf
Typical cruise speed: Mach 0.85

The propulsion system is composed of two Rolls Royce turbofan engines (BR710A2-20), mounted in an aft-fuselage configuration [29].

This aircraft is an improved version of the Global 5000, offering higher cruise speed, increased range, improved cabin layout, and lighting. The range increase is achieved by the addition of a 1486 lb fuel tank at the wing root [30].

The NetJets Europe Global 6000 fleet is composed by seven aircraft, with an average of 5 years of operation.

4.4.1 Corrosion Findings

All the corrosion findings collected in the database were, except for one unscheduled event, found in all the 15, 30 and 60 inspection blocks, performed until the moment of this revision. The corrosion findings database results are shown in Table 4.1.

As this is a relatively new fleet, it has a low number of corrosion findings (57 findings). With only two aircraft accomplishing the 60-month inspection block, where the level of inspection is higher when compared with the 15 and 30 inspection blocks, it is possible to observe that the

[3] Theoretical range with NBAA IFR reserves, ISA, M 0.85, 8 pax/4 crew. Actual range will be affected by speed, weather, selected options and other factors [29].

Table 4.1: Corrosion findings overview of the Global 6000 fleet.

ATA CHAPTER	AIRCRAFT							Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	
21 Air Conditioning	1	-	-	-	-	-	-	1
23 Communications	-	2	-	-	-	-	-	2
25 Equipment/Furnishing	1	2	-	-	-	-	-	3
27 Flight Controls	6	4	-	-	-	-	-	10
32 Landing Gear	-	-	1	-	-	-	-	1
33 Lighting	1	-	-	-	-	-	-	1
38 Water/Waste	2	1	-	-	-	-	-	3
52 Doors	1	1	-	-	-	-	-	2
53 Fuselage	4	1	-	-	-	-	-	5
55 Stabilizers	3	2	-	-	-	-	-	5
57 Wings	5	14	-	-	-	2	-	21
78 Exhaust	1	2	-	-	-	-	-	3
Total	25	29	1	-	-	2	-	57

aircraft #1 and aircraft #2 have the highest number of corrosion findings, with 25 and 29 findings, respectively.

Relatively to the number of corrosion findings by ata chapter, it is possible to verify that the four locations with the largest number of findings are: wings, 21 findings (37%); flight controls, 10 findings (18%); and fuselage and stabilizers, both with 5 findings (9%).

In the wings, corrosion was found with greater impact in locations such as flap and slat tracks surfaces. Other corrosion findings, with less impact, were found in flap fairings, ground and multifunction spoilers and ailerons, where corrosion was detected in some of the hardware, such as bolts and nuts (on-condition components).

Concerning the flight controls, corrosion was found in components such as flap torque tubes, bearings in the rudder power control unit (PCU), and in rivets, bearings and bushings in the elevator PCU.

Regarding the fuselage, corrosion was found under some panel attaching components. Components, such as nuts, plates, and screws, were found corroded in the horizontal stabilizer, while on the vertical stabilizer, a case of a light corroded skin was reported.

Besides the corrosion on the flap and slat tracks where, until the moment of this work, was only reported in aircraft #1 and aircraft #2, all the other corroded parts or components described above are single findings, meaning that only were found in one aircraft. Also, all the affected areas were found with light and surface corrosion, except the flap tracks, where pitting corrosion was found.

All the maintenance of the corrosion damages was performed accordingly to the aircraft structural repair manual or the aircraft maintenance manual (AMM). On-condition corroded components, such as screws, nuts, and bearings, were replaced and, where corroded areas were within damage limits, corrosion was removed, surfaces cleaned and prepared with corrosion protection, and if needed, painted.

4.4.2 Corrosion Economic and Operational Impact

The economic and operational impact of corrosion, found on the Global 6000 fleet in the inspection blocks listed in section 4.4.1, are shown in Table 4.2 and Table 4.3, respectively. The economic impact is presented in the form of cost percentage ("weight"), and the operational impact is shown in terms of labor hours or downtime.

Table 4.2: Corrosion economic impact in the Global 6000 fleet, presented as cost percentage, %. (N/A: Not Available)

ATA CHAPTER	AIRCRAFT							Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	
21 Air Conditioning	0.08	-	-	-	-	-	-	0.08
23 Communications	-	4.37	-	-	-	-	-	4.37
25 Equipment/Furnishing	0.22	0.55	-	-	-	-	-	0.77
27 Flight Controls	4.22	7.90	-	-	-	-	-	12.12
32 Landing Gear	-	-	28.81	-	-	-	-	28.21
33 Lighting	N/A	-	-	-	-	-	-	N/A
38 Water/Waste	5.89	-	-	-	-	-	-	5.89
52 Doors	0.20	0.14	-	-	-	-	-	0.34
53 Fuselage	1.30	0.10	-	-	-	-	-	1.40
55 Stabilizers	0.44	2.54	-	-	-	-	-	2.98
57 Wings	17.11	18.00	-	-	-	0.31	-	35.42
78 Exhaust	0.18	7.65	-	-	-	-	-	7.82
Total	29.63	41.25	28.81	-	-	0.31	-	100

Table 4.3: Corrosion operational impact in the Global 6000 fleet, presented as labor hours. (N/A: Not Available)

ATA CHAPTER	AIRCRAFT							Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	
21 Air Conditioning	2.0	-	-	-	-	-	-	2.0
23 Communications	-	23.0	-	-	-	-	-	23.0
25 Equipment/Furnishing	6.0	11.0	-	-	-	-	-	17.0
27 Flight Controls	62.5	78.6	-	-	-	-	-	141.1
32 Landing Gear	-	-	N/A	-	-	-	-	N/A
33 Lighting	4.0	-	-	-	-	-	-	4.0
38 Water/Waste	3.0	3.5	-	-	-	-	-	6.5
52 Doors	2.0	0.5	-	-	-	-	-	2.5
53 Fuselage	22.5	2.5	-	-	-	-	-	25.0
55 Stabilizers	10.0	60.0	-	-	-	-	-	70.0
57 Wings	415.1	407.6	-	-	-	8.4	-	831.1
78 Exhaust	3.6	18.0	-	-	-	-	-	21.6
Total	530.7	604.7	-	-	-	8.4	-	1143.8

Regarding the economic impact, it is possible to observe that the corrosion maintenance on the wings represents most of the corrosion costs, about 35% of the fleet corrosion costs. As we will see in the next section, this cost percentage is mostly due to corrosion maintenance performed on the flap tracks of the two oldest NetJets Europe Global 6000: aircraft #1 and aircraft #2.

The other two locations, where corrosion most economically affects the Global 6000 fleet, are: landing gear, with a cost percentage of about 28%, and flight controls, with a cost percentage of about 12% of the total corrosion costs of the fleet. The cost weight of the first location is entirely attributed to corrosion maintenance of the aircraft #3 nose landing gear (NLG), where corrosion was detected during an unscheduled event. In the second location, the costs are mostly associated with the corrosion maintenance of flap drive torque tubes in the aircraft #2.

When comparing the corrosion costs between aircraft, it is possible to see that the aircraft #2, is the aircraft most economically affected with corrosion maintenance, representing about 41% of the fleet corrosion costs. The other two aircraft that most contributed to corrosion costs are: aircraft #1, about 30%, and aircraft #3, about 29% of the fleet corrosion costs. Note that, even though the contribution of the two aircraft for the fleet corrosion costs is very similar, the cost percentage of the aircraft #3 is related to only one finding, while the cost percentage of the aircraft #1 is distributed by 25 findings.

Looking now at the operational impact of corrosion maintenance, it is possible to see that, in general, about 1144 of labor hours were spent in corrosion maintenance in the entire fleet. The aircraft that completed the 60-month inspection block, #1 and #2, have the highest downtime related to corrosion problems, with about 531 and 605 labor hours, respectively.

Between the areas that showed the highest impact, in aircraft downtime, are the wings with 831.1 labor hours, which represents about 73% of all the downtime related to corrosion problems. The problem reported in this area that contributes the most for this high downtime is the corrosion damage on the flap tracks, which represents 93% of the total labor hours spent in corrosion maintenance in the wings.

The flap tracks represent the biggest problem of the fleet, both economically and operationally.

4.4.3 Case Studies

Based on economic and operational factors, as well as recurrence within the fleet, the following components or structures were selected for a root cause analyses: flap tracks, nose landing gear, and passenger door actuator chain.

4.4.3.1 Flap Tracks

The flap tracks are part of the flap extension/retraction mechanism. Before the explanation of the corrosion problem in this component, it is essential to understand the importance of flaps in flight and the type of flap mechanism on this aircraft.

The flaps are a secondary flight control system and are the most common high-lift devices used on the aircraft. These surfaces, which are attached to the trailing edge of the wing, increase both lift and induced drag for any given angle of attack, allowing a compromise between high cruising speed and low landing speed [31].

The Global 6000 has a fowler flap mechanism (Figure 4.3) for the extension and retraction of the flap. With this mechanism, the flap slides back and forward on tracks. In the first portion of its extension, it increases the drag very little but increases the lift a great deal as it increases both the area and camber [31].

As the extension continues, the flap deflects downward. During the last portion of its travel, the flap increases drag with little additional increase in lift [31].

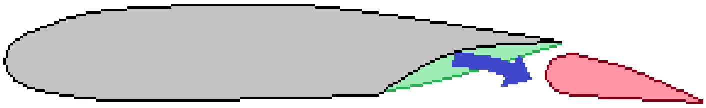

Figure 4.3: Fowler flap extension (green: retracted flap; red: extended flap) (adapted) [32].

The aircraft in question has three flaps in each wing: inboard, intermediate and outboard flaps. There are four flap tracks in each wing, located in different wing stations (Figure 4.4). The extension and retraction of the flap in this aircraft is made through two components (Figure 4.4): track and carriage. While the track is fixed to the trailing edge of the wing, the carriage is fixed to the flap. The movement of the flap is enabled through 10 rollers present on each carriage that roll on the track surface.

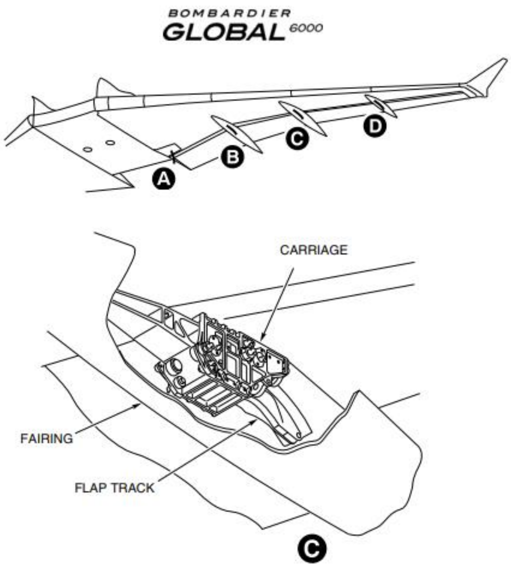

Figure 4.4: Flap tracks locations and components used in the flap extension and retraction on the Global 6000 [54].

In terms of composition, the flap track is made of a medium carbon[4], chromium-nickel-molybdenum alloy steel (Table 4.4), with the SAE[5] designation: 4330V. This is a modification of the 4330-alloy steel grade, with hardenability and other characteristics improved by the addition of vanadium [33]. The addition of vanadium to 4330V alloy steel helps it achieve high strength and hardness, also presenting good fatigue strength and toughness properties.

These properties make this alloy an excellent fit for this application since it helps to sustain the high loads exerted on the flap, when it is extended or retracted.

[4] A medium carbon steel has approximately 0.3 to 0.5% carbon content [49].
[5] The SAE steel grades system is a standard alloy numbering system, developed by Society of Automotive Engineers (SAE) International, to classify steels by their composition and physical properties [50].

Table 4.4: 4330V alloy steel composition [33].

4330V ALLOY STEEL - CHEMICAL PROPERTIES			
ELEMENT	*COMPOSITION*[6]	*ELEMENT*	*COMPOSITION*[6]
Carbon (C)	0.30 - 0.34 %	Chromium (Cr)	0.75 – 1.00 %
Manganese (Mn)	0.75 – 1.00 %	Molybdenum (Mo)	0.40 – 0.50 %
Silicon (Si)	0.15 – 0.35 %	Nickel (Ni)	1.65 – 2.00 %
Phosphorous (P)	0.035 % max	Vanadium (V)	0.05 – 0.10%
Sulphur (S)	0.035 % max		

The high levels of nickel, chromium, and molybdenum, alter the chemical structure of the steel in a way that improves the corrosion and abrasion resistance [34]. Although the alloy steel has excellent corrosion resistance properties by itself, the flap tracks also have a nickel plate on its surface, improving their corrosion resistance.

Problem Breakdown

The root cause analysis of the corrosion problem showed a problem associated with the movement of the rollers on the track surface. The fairings (Figure 4.5), aerodynamic bodies located under the wings, protect the flap track from the environment when the flap is retracted. When the flap is extended, the fairing comes down, allowing the movement of the carriage on the track, and the movement of the flap backward. In this position, the flap track is exposed to the environment, allowing debris, existent in the atmosphere or on the ground, to be deposited on the track surface.

Adding to the presence of debris in the tracks, the high loads on the flap, leads to friction between the rollers (attached to the carriages) and the track surface, when the flap movement is required.

This mechanical abrasion causes the nickel plate protection to wear out, and thus starts flaking (Figure 4.6-A). Without the nickel plate, the areas of bare metal (Figure 4.6-B), corresponding to the areas of contact of the track with the rollers (Figure 4.7), are exposed to any corrosive agent present in the environment, which in turn will lead to corrosion of the track surface.

[6] Chemical composition presented in weight percent.

Figure 4.5: Global 6000 wing (flap tracks) fairings.

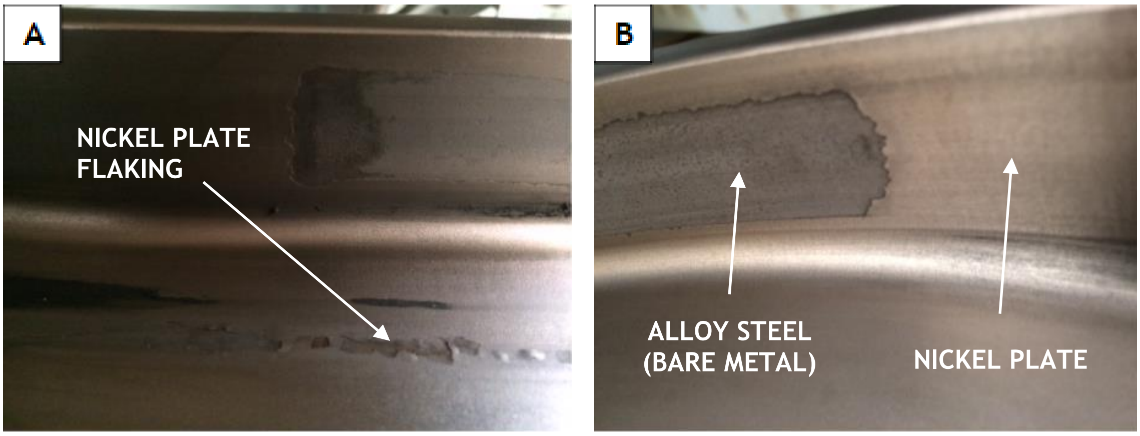

Figure 4.6: Nickel plate wear out (A - track areas with nickel plate flaking; B - track areas with and without protection). (Images obtained from NetJets Europe portfolio)

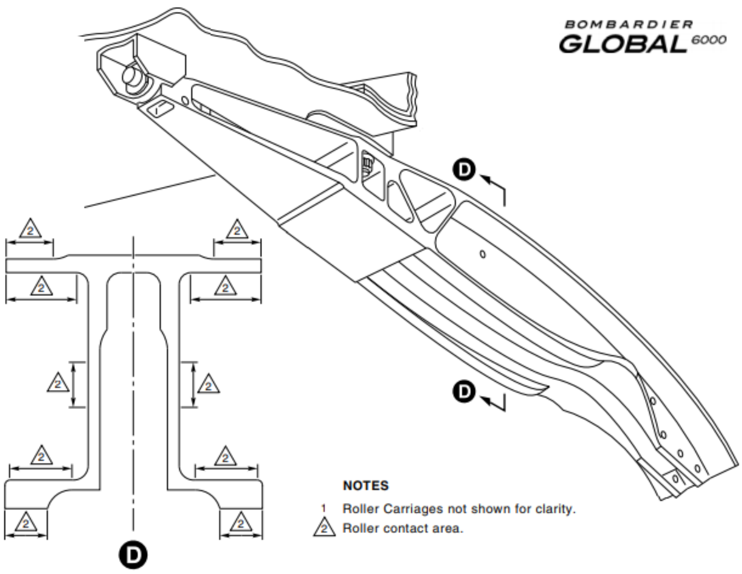

Figure 4.7: Flap track areas of contact with the rollers [55].

The corrosion present on the track is surface corrosion (Figure 4.8) and pitting (Figure 4.9), as it is visible the presence of tinny pits or holes in the steel surface.

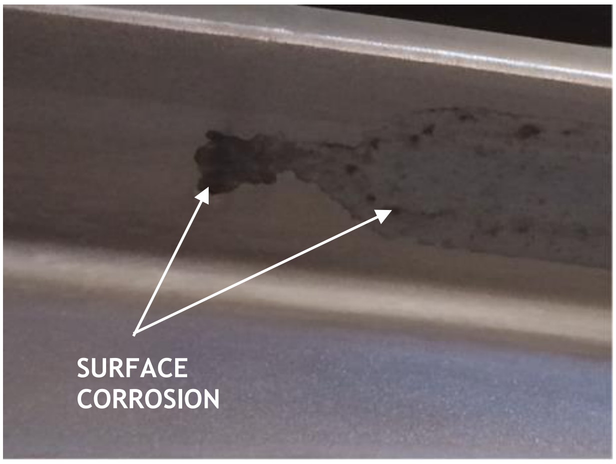

Figure 4.8: Surface corrosion (brown color) visible on the flap track surface. (Image obtained from NetJets Europe portfolio)

Figure 4.9: Tiny pits (holes) present on the flap track surface. (Images obtained from NetJets Europe portfolio).

When corrosion is found in this component, at the 60-month inspection, it is removed with a powered mechanical sandpaper, following a blending process, that involves the loss of material, and thus reduction in the material thickness. After the corrosion removal and blending process, measurements are made to the track material thickness, using a micrometer, to confirm if it is within SRM rework limits. If not, the measurements are sent to the aircraft manufacturer, for tests and evaluations, to decide if the limits can be extended, and the component labeled as serviceable, or if the component needs to be replaced.

By OEM recommendation, no type of protection or product can be applied to the affected areas (contact areas of track surface with the rollers), since there are no studies available about the effect of these products in the normal movement of the flaps. Thus, these areas are left unprotected, and the bare metal is exposed again to the environment, as the aircraft return to service. In time, this state will lead to corrosion reappearance in the flap tracks (Figure 4.10). Another limitation imposed by the OEM is that, the reapplication of nickel plate to the track surface cannot be performed by any company or institution other than the OEM, since, if not performed following right standards, it can lead to the appearance of nickel plate flakes in the rollers, disabling the normal movement of the flaps.

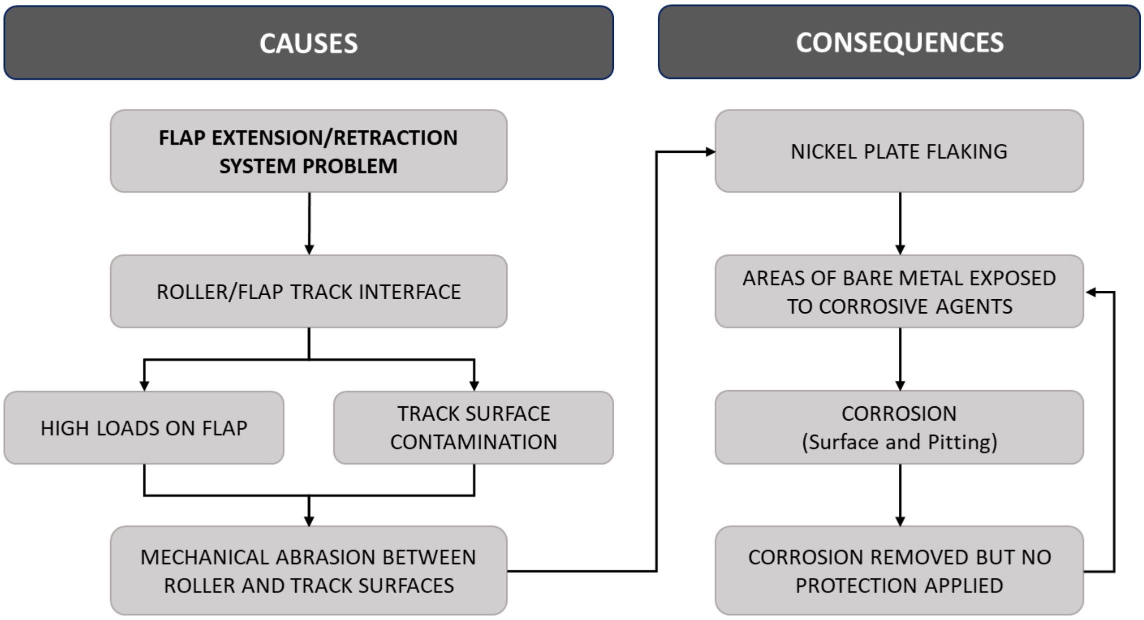

Figure 4.10: Flap track corrosion problem diagram.

From the aircraft manufacturer, it is known that this problem does not only affect the Global 6000 aircraft, but the entire Global family. Also, until the moment, no flap track was replaced due to track material thickness removal exceeded the limits for a serviceable component.

Was also found that, at the 3000 flight hours inspection, when performing the Maintenance Planning Document (MPD) task “Detailed Inspection of the Flap Rollers,” where the procedure to inspect the tracks for marks or cracks caused by the rollers is performed, nothing was reported about the nickel plate condition. Since the aircraft manufacturer is unable to replace the areas without the nickel plate, there are no procedures to report the protection condition. With nothing reported at an earlier[7] stage of inspections, it is unknown if, at the time of this inspection, the plate is still intact.

[7] NetJets Europe considers, as metric rule, an average of 1000 flight hours per year. Using this metric rule, the 3000 flight hours inspection is performed about every 3 years, performing the first inspection 2 years earlier than the first 60-month inspection.

Economic and Operational Impact

This damage can only be found at the 60-month inspection where the task "Detailed Inspection of the Flap Track Rails – WS47.80, WS178.00, WS287.00 and WS404.00", present in the MPD, is performed. Since only two aircraft have reached this inspection block, at the time of this work, only these have shown this problem: aircraft #1 and aircraft #2.

The percentages related to corrosion maintenance costs and respective labor hours for each aircraft and fleet are shown in Table 4.5. Being the biggest problem, until the moment, found on the Global 6000 fleet, this problem represents about 33% of the fleet corrosion costs. We observe that this problem represents 56%, more than half of the corrosion costs of the aircraft #1, while in the aircraft #2, this problem represents 39 % of the corrosion costs of this aircraft, values that are significant for considering it as a concerning problem on the Global 6000 fleet.

Table 4.5: Economic and operational impact of the flap tracks corrosion problem.

	A/C #1	A/C #2	Fleet
No. of Findings	1	1	2
Corrosion costs related to flap tracks in relation with the total corrosion costs (respective aircraft)	56%	39%	-
Corrosion costs related to flap tracks in relation with the total corrosion costs (fleet)	17%	16%	33%
Labor Hours	405	371	776

In terms of downtime, a total of 776 hours were spent in corrosion maintenance, in both aircraft, about 68% of all the labor hours spent in corrosion maintenance in the entire fleet. It is important to note that the high maintenance costs and labor hours are associated with difficulties encountered in the removal and cleaning of corrosion from the alloy steel.

Proposed Measure

Since the preventive approach could not be considered, such as the use of CICs, due to the lack of studies on the effects of these products in the normal operation of the flap, another approach had to be studied.

The measure studied and proposed, is a corrosion control measure and consists of two changes. The first was the addition of a procedure to inspect the flap tracks, along with the condition of the nickel plate, to the MPD task "Detailed Inspection of the Flap Rollers". The second change consisted in the task interval change, from being performed every 3000 flight hours to a first inspection being performed when reached the 3000 flight hours, and then repeat the inspection every 1500 flight hours. Although, this interval change could signify a partial coverage of the inspection costs by the operator, an early detection of corrosion and consequent repair could prevent a more costly, extensive and invasive repair in a later inspection or detection. Note that the access that is performed to inspect the flap rollers is the same performed to inspect the flap tracks, an advantage in terms of inspection costs and inspection labor hours.

As we know from Chapter 2, when the corrosion products do not form a protective film, the corrosion growth usually increases exponentially with time, given the proper conditions. In the graphic[8] (Figure 4.11), it is possible to observe three possible states: without inspections, the current state of inspections (60-month inspections) and the proposed measure.

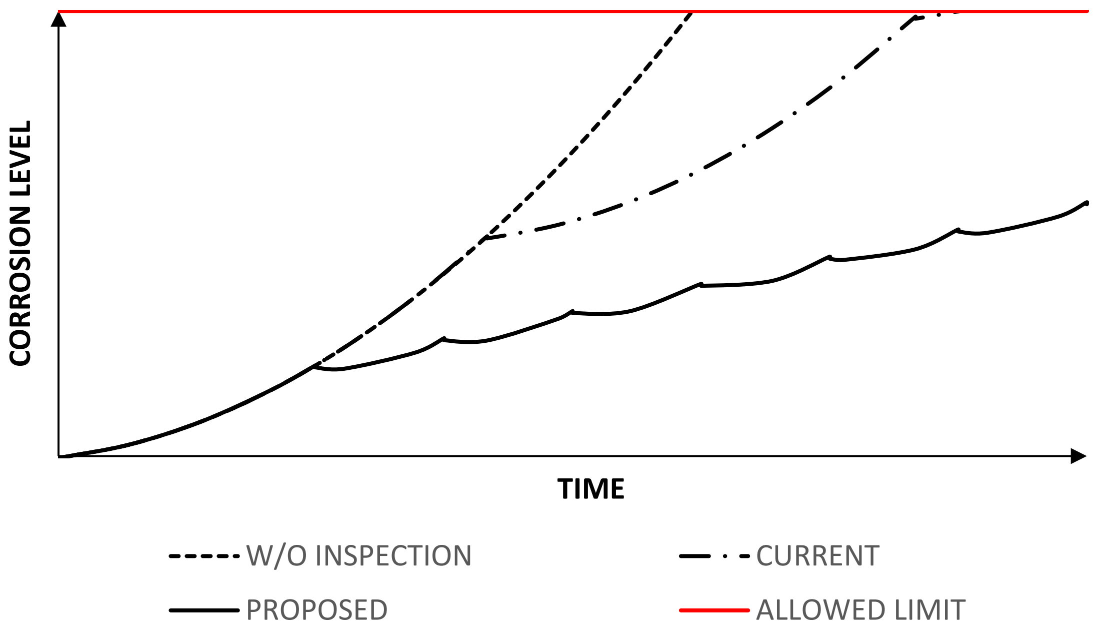

Figure 4.11: Corrosion evolution with time for three cases: without inspection, current inspection interval and proposed inspection interval.

Comparing the current state of inspections with the proposed measure, it is possible to extend the service life of the component with the proposed measure. An early corrosion detection and treatment, at a stage of low corrosion growth and where corrosion has not affected a lot of material in depth, it is possible to avoid replacement costs of a flap track at an earlier stage, by extending the service life of the component.

[8] The graphic in Figure 4.11 was used for reference only, with intent of demonstrate the objective of the proposed measure. The graphic does not represent in any way the corrosion evolution on the flap tracks for the operational area of the aircraft.

4.4.3.2 Nose Landing Gear

The purpose of the landing gear in an aircraft is to provide a suspension system during taxi, takeoff, and landing, absorbing and dissipating the kinetic energy of landing impact, thereby reducing the impact loads transmitted to the airframe [35]. It also facilitates breaking of the aircraft using a wheel braking system and provides directional control of the aircraft on ground using a wheel steering system. It is often made retractable to minimize the aerodynamic drag on the aircraft while flying [35].

A landing gear comprises of many structural components, such as shock absorber, bogie beam/trailing arm, axle, torque links, wheel, tire, etc., and system components, such as brake unit, antiskid system, retraction system components. The nose landing gear (Figure 4.12) will have additional elements like a steering actuator and steering mechanism.

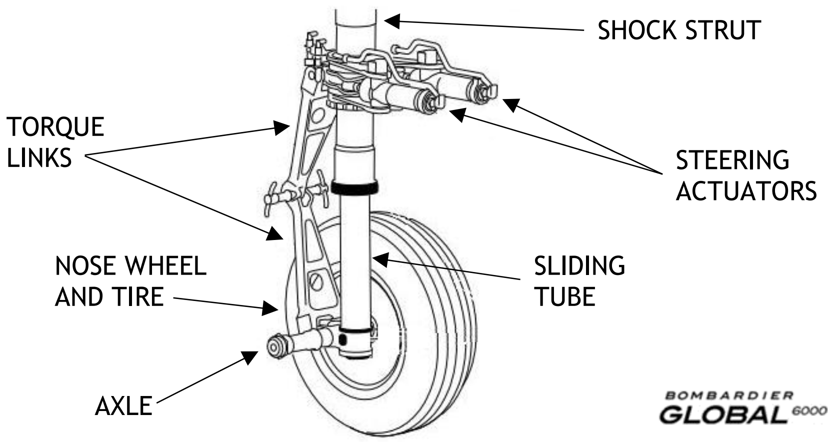

Figure 4.12: Global 6000 nose landing gear structural components (adapted) [54].

The Global 6000 has a tricycle landing gear configuration (Figure 4.13), with the main landing gear located below the fuselage-to-wing fairing, and the nose landing gear located at the nose of the aircraft. This configuration allows [31]:

- More forceful application of the brakes during landing at high speeds without causing the aircraft to nose over;
- Better forward visibility for the pilot during takeoff, landing, and taxiing;
- To prevent ground looping (swerving) by providing more directional stability during ground operation since the aircraft's center of gravity (CG) is forward of the main wheels.

Figure 4.13: Global 6000 landing gear configuration (A - tricycle landing gear configuration; B - nose landing gear; C - main landing gear).

Problem Breakdown

The corrosion damage was found during an unscheduled event, which means that was not found during a programmed MPD inspection task. During the towing of the aircraft #3, at Paris Airport (CDG), a towing bushing broke, which had to be replaced. It was during the replacement of the bushing, that was found corrosion in three components at the bottom part of the nose landing gear: axle, sliding tube (part of the suspension system of the nose landing gear, which connects perpendicularly to the axle) and the retaining bolt (connects the axle to the sliding tube).

After the detection of corrosion, the components were sent to OEM headquarters for tests and evaluations. The OEM concluded that these areas could not have rework limits, and thus, all three components had to be replaced.

Investigating maintenance reports, related to the MPD task "General Visual Inspection of the Nose Landing Gear" achieved every 450 landings, in which an inspection of the seals condition in the nose landing gear is performed, it was possible to find that in two of these inspections (Table 4.6), the sealants in the surroundings of the axle/sliding tube were found either damaged or missing.

The absence of the sealant could have allowed corrosive agents, such as water from rain or washes, or runway de-icing products, to enter through the spaces of damaged or missing sealant.

Table 4.6: Sealant problems reported during the 450 landings inspections.

DATE	INSPECTIONS				
	2014	2015	2016	2017	2018
FINDING	*“SEALANT DAMAGED* ON LOWER RING OF NOSE LANDING GEAR”	“FOUND *SEALANT MISSING* ON NLG STRUT ASSY”	-	-	-

The presence of these corrosive agents between the axle and the sliding tube allowed the corrosion process to start. The corrosion (light brown and white areas) was found in the interior surface of the axle front cylinder (Figure 4.14), sliding tube exterior surface (Figure 4.15), holes of both axle and sliding tube (Figure 4.14 and Figure 4.15) and the retaining bolt (Figure 4.16) that connects the axle to the sliding tube.

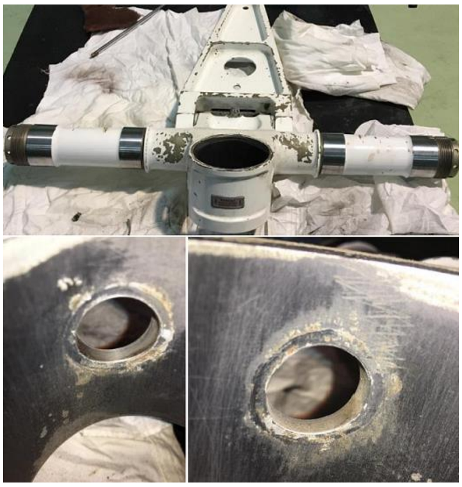

Figure 4.14: Corrosion damage detected in the holes and interior surface of the axle front cylinder. (Images obtained from NetJets Europe portfolio)

Figure 4.15: Corrosion damage found in the holes and exterior surface on the bottom part of the sliding tube. (Images obtained from NetJets Europe portfolio)

Figure 4.16: Corroded retaining bolt. (Image obtained from NetJets Europe portfolio)

As said before, this was found during an unscheduled event in the aircraft #3. For the other aircraft of the fleet, the existence of this problem can only be verified through the MPD task “NLG Restoration”, accomplished at the 120-month (10 years) inspection, where all the components of the landing gear are removed, for a thorough inspection. At the time of this work, none of the other 6 aircraft have reached this inspection interval.

Economic and Operational Impact

At the time of this revision, only one aircraft nose landing gear was found corroded in the areas mentioned before, making this a non-recurrent case study.

Being the only corrosion finding in aircraft #3, since this aircraft had not reached the 60-month inspection block at the time of this work, the maintenance costs related with this finding represent the total corrosion costs for this aircraft. Comparing with the fleet corrosion costs, this finding represents 29 % of that total. The maintenance costs associated with this corrosion damage are related to the replacement of the affected components, since no rework was allowed by the OEM. Since the replacement of the component was performed by the OEM, the labor hours for this work were not available.

Besides having a significant economic impact on corrosion costs, this damage could represent an airworthiness problem, if undetected, due to the structural importance of the landing gear during takeoff and landing.

Proposed Measure

One of the measures considered, with the objective of corrosion control/monitoring, was to reduce the interval of the task “NLG Restoration”, currently performed every 120 months (10 years). This propose was discarded because, besides the fact that every MPD task interval change could signify the total inspection costs coverage by the operator, this type of inspection would also have a significant impact in aircraft downtime, and thus in aircraft availability, since it requires the removal of all the nose landing gear components for inspection.

The presented proposal for this problem focuses on the inspection of the nose landing gear sealants. In addition to the existent MPD task “General Visual Inspection of the Nose Landing Gear”, where the sealants are currently inspected every 450 landings, it was proposed the introduction of the procedure “Inspection of the general condition of the sealant for signs of peeling or cracks” (Figure 4.17) to the MPD task “Lubrication of the Nose Landing Gear (NLG) and Components”, performed every 250 flight hours. This addition allows better control and monitoring of the sealants condition, important to prevent the entry of corrosive agents in the affected areas. This proposal, like the one presented for the flap tracks, could also signify a total or partial coverage of the inspection costs by the operator, but with less cost and downtime impact, since this proposal only involves a general visual inspection of the sealants.

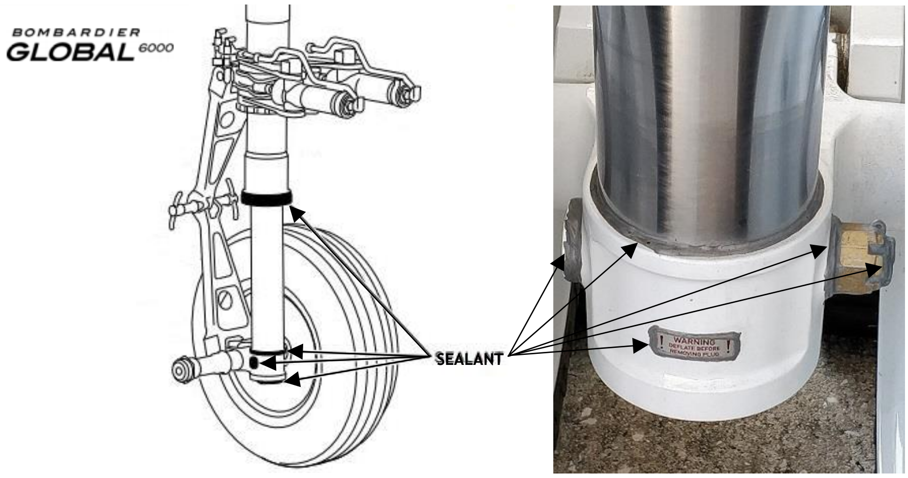

Figure 4.17: Location of the nose landing gear sealants (adapted) [54].

4.4.3.3 Passenger Door Actuator Chain

The passenger door, located in the front left side of the fuselage, is used by the passengers and crew (pilots and cabin crew) to enter the aircraft. Like most of the business jet aircraft, the Global 6000 passenger door has a built-in staircase (Figure 4.18), and the opening and closing of the door is performed on a horizontal axis.

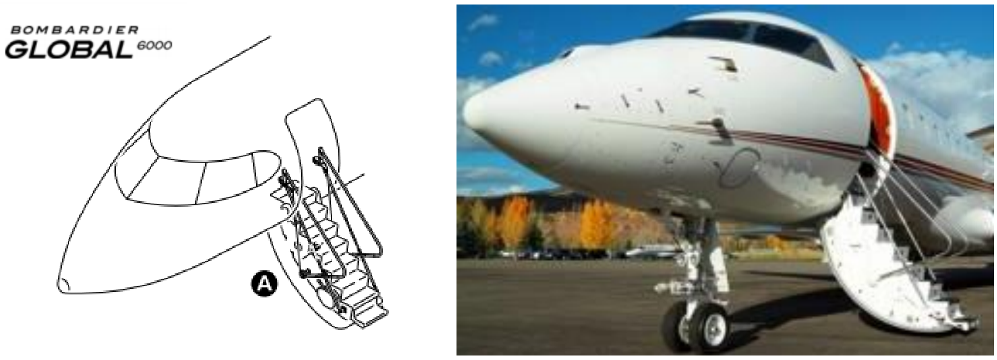

Figure 4.18: Global 6000 passenger door (adapted) [56, 57].

Problem Breakdown

The actuator located under the staircase of the passenger door (Figure 4.19), is an electrical actuator responsible for the opening and closing of the door.

Figure 4.19: Location of the passenger door actuator, under the staircase [56].

The corrosion problem was found in the chain (Figure 4.20) that connects two sprockets, one attached to the actuator and the other attached to a rod. The movement of the chain, generated by the electrical actuator, between the two sprockets, allows the door to open or close.

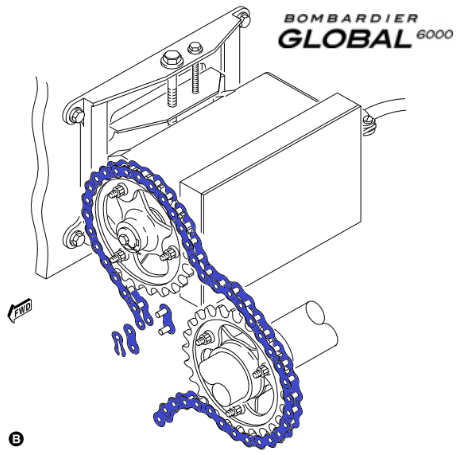

Figure 4.20: Passenger door actuator chain (in blue) (adapted) [56].

According to OEM documentation, the chain is supplied with a coating of heavy petroleum grease, adequate for slow and light load applications, such as this one. However, due to a high frequency of use of NetJets Europe aircraft, the multiple times that the door is opened and closed may be affecting the condition of the coating, allowing corrosion to develop.

Economic and Operational Impact

Corrosion on the actuator chain was found at the 60-month inspection. There are no maintenance tasks involved, such as cleaning or re-protection of the component, since in both cases (aircraft #1 and aircraft #2) the chain had to be replaced.

The cost percentages and labor hours, presented in Table 4.7, are related to the removal of the corroded chain and installation of the new chain. In the same table, it is possible to observe that this problem has a low impact at an economic and operational level. For the aircraft #1, this problem represents less than 1% (exactly 0.67%) of the corrosion costs for this aircraft. For the aircraft #2, such as for aircraft #1, this problem also represents less than 1% (exactly 0.42%) of the corrosion costs for this aircraft. In terms of downtime, in aircraft #1, it was spent 2 labor hours, and in aircraft #2, it was spent 0.5 labor hours replacing the chain. The discrepancy between the labor hours on the two aircraft can be related to unavailability of the component or difficulties in the removal or installation of the component.

Although this problem has a low impact, both economic and operational, it was considered a case study due to the recurrence within the fleet. Another determinant factor was the constant replacement of the chains, whenever corrosion is found, increasing aircraft downtime.

Table 4.7: Economic and operational impact of the actuator chain corrosion problem.

	A/C #1	A/C #2	Fleet
No. of Findings	1	1	2
Corrosion costs related to actuator chain in relation with the total corrosion costs (respective aircraft)	0.67%	0.42%	
Corrosion costs related to actuator chain in relation with the total corrosion costs (fleet)	0.20%	0.17%	0.37%
Labor Hours	2	0.5	2.5

Proposed Measure

Due to the high frequency of operation of NetJets Europe aircraft, which means that the passenger door is used multiple times, the condition of the coating present in the chain was put into question.

To solve this problem, the chain should be re-protected from time to time, allowing the service life of the component to be extended. When contacting the OEM about this situation, it was recommended the lubrication of the chain, with an SAE 30 (Oil Viscosity VG100) lubricant, applied with an aerosol.

Without creating a new task with a defined interval for the chain lubrication, which could lead to an increase in inspection costs and inspection time, the procedure of lubrication of the passenger door actuator chain should be added to an existent task. With this in mind, it was proposed the addition of the procedure to the MPD task "Lubrication of the Passenger Door", performed every 1500 flight hours. In this task, the access performed for the lubrication of multiple door components is the same performed for the lubrication of the chain, if this one was performed in an individual MPD task. The introduction of the procedure in an existent task does not have a significant impact on the maintenance costs and labor hours.

4.5 Falcon 2000ex Easy

The Falcon 2000ex Easy (Figure 4.21) is an aircraft manufactured by Dassault Aviation, with a low wing, cruciform tail, and a tricycle landing gear configuration. The aircraft present the following specifications and performance [36, 37]:

Crew: 2
Passengers: up to 10
Height: 23 ft 2 in
Wingspan: 63 ft 5 in
Length: 66 ft 4 in
Maximum Range: 4045 nm
Maximum Fuel Weight: 16660 lb
Maximum Payload: 6510 lb
Maximum Takeoff Weight: 42200 lb
Service Ceiling: 47000 ft

Figure 4.21: NetJets Europe Falcon 2000ex Easy aircraft (CS-DLB) [58].

Engine: PW308C
Thrust: 7000 lbf
Typical cruise speed: Mach 0.74

The propulsion system is composed of two Pratt & Whitney Canada turbofan engines (PW308C), mounted in an aft-fuselage configuration [36].

The Falcon 2000ex Easy is a commercial designation of the Falcon 2000Ex (variant certified in 2003 with Pratt & Whitney Canada PW308C turbofan engines), with an enhanced avionics system and changes to pressurization and oxygen system, certified in 2004 [36].

The NetJets Europe Falcon 2000ex Easy fleet is composed by ten aircraft, with an average of 12 years of operation.

4.5.1 Corrosion Findings

The exercise performed for the Global 6000 fleet, was also performed for the Falcon 2000ex Easy fleet. The corrosion findings, found in all the A+ (8 month), Z (24 month), C (72 month) and 2C (144 month) inspection blocks, performed until the moment of this revision, are summarized in Table 4.8, by ata chapter (area) and by aircraft.

Compared with the previous fleet, the Falcon 2000ex Easy fleet is an older fleet, which results in more detailed inspections performed and consequently, more corrosion findings: 1457.

In the Falcon 2000ex Easy fleet, all the aircraft have performed several A+ and Z inspection blocks, and at least one C inspection block. The 2C inspection block was only achieved by the four older aircraft of the fleet: aircraft #1, aircraft #2, aircraft #3, and aircraft #4. It is important to refer that the level of inspection increases from the A+ to the 2C inspection block.

Relatively to the number of corrosion findings by ata chapter, we observe that the three locations that are most affected by corrosion are: landing gear, 407 findings (28%), fuselage, 253 findings (17%), and wings, 234 findings (16%).

Table 4.8: Corrosion findings overview in the Falcon 2000ex Easy fleet.

ATA CHAPTER	AIRCRAFT										Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	A/C #8	A/C #9	A/C #10	
20 Standard Practices	5	3	4	3	2	3	3	4	3	1	31
21 Air Conditioning	3	1	5	4	2	1	-	1	2	1	20
23 Communications	4	-	1	1	1	-	1	4	-	2	14
24 Electrical Power	1	2	3	3	4	1	2	3	2	-	21
25 Equipment/Furnishing	4	1	3	-	2	1	1	-	2	2	16
26 Fire Protection	-	-	-	-	1	-	-	-	-	-	1
27 Flight Controls	3	5	3	7	-	4	7	8	2	9	48
28 Fuel	4	2	3	-	2	-	-	5	1	-	17
29 Hydraulic Power	6	5	6	1	-	4	2	2	8	-	34
30 Ice & Rain	2	2	2	-	-	-	-	-	1	-	7
32 Landing Gear	28	38	32	29	46	33	35	66	58	42	407
33 Lighting	2	4	5	1	2	2	1	3	-	2	22
34 Navigation	3	2	2	-	1	1	1	2	1	3	16
36 Pneumatic	-	1	-	1	-	-	-	-	1	-	3
38 Water/Waste	5	2	6	3	2	4	2	2	2	2	30
49 Auxiliary Power	1	1	-	2	-	-	1	-	-	1	6
51 Structures	-	2	-	-	-	-	-	-	-	-	2
52 Doors	8	6	13	11	7	6	8	6	3	6	74
53 Fuselage	27	22	25	17	18	27	27	45	17	28	253
54 Nacelles/Pylons	3	2	2	4	1	4	3	6	3	3	31
55 Stabilizers	2	11	13	5	1	11	2	13	7	6	71
56 Windows	-	-	-	-	-	1	-	-	-	-	1
57 Wings	18	17	15	22	11	25	23	45	29	29	234
71 Power Plant	1	1	4	-	-	-	-	-	-	1	7
72 Engine	2	1	-	2	1	-	1	-	-	-	7
78 Exhaust	9	8	8	11	3	8	10	10	7	9	83
79 Oil	-	-	-	-	-	-	1	-	-	-	1
Total	141	139	155	127	107	136	131	225	149	147	1457

The landing gear area has the highest number of findings since this area is exposed to many corrosive agents, such as mud, water, salt, gravel, and other flying debris present in runways. In this fleet, corrosion is usually found in several hydraulic components in the landing gear wheel well, components in the landing gear doors, torque links, manifolds, plugs, among other components.

In the second most affected area, the fuselage, corrosion can be found in several compartment floor beams, fuselage frames, and fuselage skins or panels. In the third most affected location, the wings, corrosion was mostly found in flap rollers, under bonding plates in various locations, aileron components, among others.

All the maintenance of the corrosion findings was performed accordingly to the manufacturer SRM or AMM. On-condition corroded components, such as screws, nuts, and bearings, were replaced and, where corroded areas were within damage limits, corrosion was removed, surfaces cleaned and prepared with corrosion protection, and if needed, painted.

4.5.2 Corrosion Economic and Operational Impact

First, is vital to refer that, due to the unavailability of data, related to corrosion costs and labor hours, at the time of this work, discrepancies may be found in the economic and operational impact tables. All the conclusions and observations performed, were based on the available data.

The economic and operational impact of corrosion maintenance, performed on the Falcon 2000ex Easy fleet, in the inspection blocks listed in section 4.5.1, are shown in Table 4.9 and Table 4.10, respectively. The economic impact is shown in the form of cost percentage ("weight"), while the operational impact is shown in terms of labor hours or downtime.

It is possible to conclude, from Table 4.9, that the engine exhaust area represents the most economically affected area, even though this area does not present the highest number of findings (83 findings). The corrosion costs of this area represent 48.22%, almost half, of the fleet corrosion costs. The reason for this high economic impact is attributed to the corrosion damages found in the nozzle and doors of the thrust reverser, that affects the entire fleet.

Following the engine exhaust area, the other two locations that contribute the most for the fleet corrosion costs are: fuselage, with a cost percentage of 11.11%, and wings, with a cost percentage of 10.73% of the fleet corrosion costs.

Table 4.9: Corrosion economic impact in the Falcon 2000ex Easy fleet, presented as cost percentage, % (N/A: Not Available).

ATA CHAPTER	AIRCRAFT										Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	A/C #8	A/C #9	A/C #10	
20 Standard Practices	N/A	N/A	N/A	N/A	N/A	N/A	0.01	N/A	N/A	N/A	0.01
21 Air Conditioning	0.05	N/A	N/A	N/A	0.18	0.09	-	0.01	N/A	N/A	0.34
23 Communications	0.20	-	N/A	N/A	N/A	-	N/A	0.04	-	N/A	0.25
24 Electrical Power	0.78	N/A	N/A	N/A	3.01	N/A	N/A	0.02	0.01	-	3.82
25 Equipment/Furnishing	0.06	N/A	N/A	-	0.02	N/A	N/A	-	N/A	N/A	0.08
26 Fire Protection	-	-	-	-	N/A	-	-	-	-	-	N/A
27 Flight Controls	0.01	1.01	N/A	1.51	-	N/A	0.01	0.04	N/A	N/A	2.59
28 Fuel	0.02	0.02	N/A	-	0.01	-	-	0.03	N/A	-	0.09
29 Hydraulic Power	0.72	0.93	N/A	N/A	-	N/A	0.01	N/A	N/A	-	1.66
30 Ice & Rain	N/A	0.06	N/A	-	-	-	-	-	N/A	-	0.06
32 Landing Gear	2.72	2.64	N/A	1.86	0.45	0.44	0.10	0.43	0.16	0.03	8.83
33 Lighting	0.15	0.05	N/A	N/A	N/A	N/A	N/A	0.01	-	N/A	0.21
34 Navigation	1.78	0.02	N/A	-	N/A	N/A	N/A	0.02	N/A	N/A	1.82
36 Pneumatic	-	N/A	-	N/A	-	-	-	-	N/A	-	N/A
38 Water/Waste	N/A	0.01	N/A	N/A	0.01	0.09	0.01	N/A	N/A	0.01	0.14
49 Auxiliary Power	0.03	0.08	-	N/A	-	-	N/A	-	-	N/A	0.10
51 Structures	-	N/A	-	-	-	-	-	-	-	-	N/A
52 Doors	0.68	0.11	N/A	0.91	0.06	0.01	N/A	0.02	0.01	N/A	1.80
53 Fuselage	1.86	5.69	N/A	2.65	0.41	0.03	0.10	0.37	N/A	N/A	11.11
54 Nacelles/Pylons	0.03	0.18	N/A	0.21	N/A	N/A	N/A	0.61	N/A	N/A	1.03
55 Stabilizers	0.04	3.66	N/A	N/A	0.01	N/A	0.01	0.07	N/A	N/A	3.78
56 Windows	-	-	-	-	-	N/A	-	-	-	-	N/A
57 Wings	8.02	1.10	N/A	1.20	0.07	N/A	0.03	0.31	N/A	N/A	10.73
71 Power Plant	0.28	N/A	N/A	-	-	-	-	-	-	1.29	1.58
72 Engine	0.18	N/A	-	N/A	1.05	-	N/A	-	-	-	1.23
78 Exhaust	7.31	32.7	N/A	7.81	0.17	0.12	0.02	0.03	0.01	N/A	48.22
79 Oil	-	-	-	-	-	-	0.53	-	-	-	0.53
Total	24.93	48.2	N/A	16.16	5.45	0.78	0.84	2.03	0.19	1.34	100

Table 4.10: Corrosion operational impact in the Falcon 2000ex Easy fleet, presented as labor hours (N/A: Not Available).

ATA CHAPTER	AIRCRAFT										Total
	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	A/C #8	A/C #9	A/C #10	
20 Standard Practices	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
21 Air Conditioning	1.3	N/A	N/A	N/A	5.3	3.5	-	N/A	N/A	N/A	10.0
23 Communications	14.5	-	N/A	N/A	N/A	-	N/A	N/A	-	N/A	14.5
24 Electrical Power	2.0	N/A	N/A	N/A	7.8	N/A	N/A	N/A	N/A	-	9.8
25 Equipment/Furnishing	5.0	N/A	N/A	-	N/A	N/A	N/A	-	N/A	N/A	5.0
26 Fire Protection	-	-	-	-	N/A	-	-	-	-	-	N/A
27 Flight Controls	N/A	90.2	N/A	134.5	-	N/A	N/A	N/A	N/A	N/A	224.7
28 Fuel	N/A	1.8	N/A	-	N/A	-	-	N/A	N/A	-	1.8
29 Hydraulic Power	29.3	41.8	N/A	N/A	-	N/A	N/A	N/A	N/A	-	71.0
30 Ice & Rain	N/A	5.4	N/A	-	-	-	-	-	N/A	-	5.4
32 Landing Gear	196.6	162.1	N/A	10.7	16.9	11.0	N/A	N/A	N/A	N/A	397.3
33 Lighting	9.0	1.5	N/A	N/A	N/A	N/A	N/A	N/A	-	N/A	10.5
34 Navigation	3.5	N/A	N/A	-	N/A	N/A	N/A	N/A	N/A	N/A	3.5
36 Pneumatic	-	N/A	-	N/A	-	-	-	-	N/A	-	N/A
38 Water/Waste	N/A	N/A	N/A	N/A	N/A	4.5	N/A	N/A	N/A	N/A	4.5
49 Auxiliary Power	2.4	6.8	-	N/A	-	-	N/A	-	-	N/A	9.2
51 Structures	-	N/A	-	-	-	-	-	-	-	-	N/A
52 Doors	52.9	7.9	N/A	25.1	N/A	N/A	N/A	N/A	N/A	N/A	85.8
53 Fuselage	146.7	462.7	N/A	223.9	N/A	2.5	N/A	N/A	N/A	N/A	835.9
54 Nacelles/Pylons	2.4	15.8	N/A	19.0	N/A	N/A	N/A	51.3	N/A	N/A	88.5
55 Stabilizers	3.4	325.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	329.0
56 Windows	-	-	-	-	-	N/A	-	-	-	-	N/A
57 Wings	79.2	74.2	N/A	106.9	N/A	N/A	N/A	N/A	N/A	N/A	260.3
71 Power Plant	16.8	N/A	N/A	-	-	-	-	-	-	115.1	131.8
72 Engine	N/A	N/A	-	N/A	N/A	-	N/A	-	-	-	N/A
78 Exhaust	321.2	1161.2	N/A	141.6	15.6	10.6	N/A	N/A	N/A	N/A	1650.1
79 Oil	-	-	-	-	-	-	32.5	-	-	-	32.5
Total	885.9	2357.1	N/A	661.6	45.5	32.1	32.5	51.3	N/A	115.1	4181.1

Is not possible to make a proper comparison of corrosion costs between aircraft, since the unavailability of data, leaves some aircraft with a very low or inexistent economic impact, where was expected a low to moderate impact.

In terms of operational impact, the area that has the highest impact in aircraft downtime is the engine exhaust area, with 1650.1 labor hours (39%). This high number of labor hours is mostly associated with the maintenance of corrosion damages on the thrust reversers. Other areas, such as the fuselage and landing gear, also have a significant impact in aircraft downtime, with 835.9 (20%) and 397.3 (10%) labor hours, respectively.

As succeeded for the economic impact, the unavailability of data does not allow a proper comparison of downtimes between aircraft.

It is possible to conclude that the engine exhaust area, or more specifically, the thrust reversers represent the biggest problem of the fleet, both economically and operationally.

4.5.3 Case Studies

Based on economic and operational factors, as well as recurrence within the fleet, the following components or structures were selected for root cause analyses: thrust reverser, horizontal stabilizer, and mechanical servicing compartment floor beam.

4.5.3.1 Thrust Reverser

The Falcon 2000ex Easy has a propulsion system composed of two Pratt & Whitney Canada PW308C turbofan engines, mounted on an aft-fuselage configuration (Figure 4.22).

Figure 4.22: Falcon 2000ex Easy aft-fuselage engine configuration [59].

Being this a jet aircraft, it has high kinetic energy during the landing phase, because of weight and speed. This energy is difficult to dissipate because, even on the ground, the engines continue to produce forward thrust, with the power levers at idle [32]. Even though wheel brakes usually can cope, another method should exist to counter the forward thrust produced by the engines [32]. This is achieved by the drag provided by thrust reverser.

The thrust reverser is a device fitted in the engine exhaust system, which effectively reverses the flow of the exhaust gases [32]. The aircraft in question has a target-type thrust reverser (Figure 4.23), where clamshell doors swivel from the stowed position at the engine tailpipe, to block all the outflow and redirect some component of the thrust reverser [32]. At the forward thrust position, these doors are part of the engine nozzle.

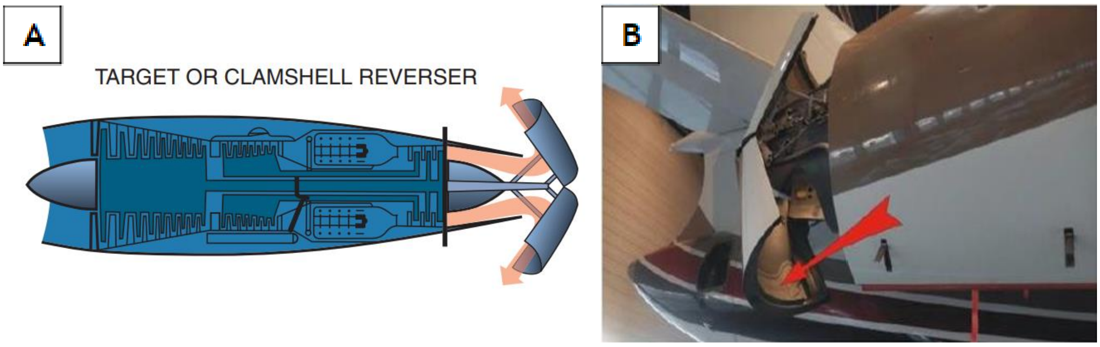

Figure 4.23: Target or Clamshell thrust reverser (A – Target or clamshell thrust reverser configuration; B – Falcon 2000ex Easy thrust reverser in the open position) (adapted) [32].

Problem Breakdown

At the A+ inspections (every 8 months), corrosion was found in two locations of the thrust reverser (Figure 4.24): doors (1) and nozzle (2). The exhaust stream from the engine contacts the interior surface of both components, located at the end of the engine nacelle.

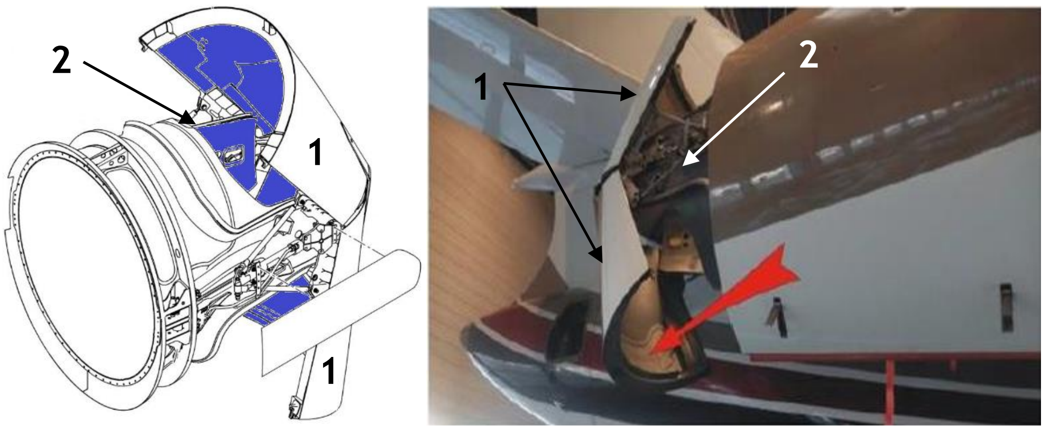

Figure 4.24: Falcon 2000ex Easy thrust reverser (1 - doors; 2 – nozzle; in blue: corroded areas) (adapted) [60].

According to aircraft manufacturer information, this problem has been seen in several in-service aircraft, namely that the interior surface of the thrust reverser assembly (Figure 4.25-A and Figure 4.25-B) show signs of premature corrosion. After the completion of tests on material samples taken from the thrust reverser, it was concluded that, under certain circumstances, sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) can mix with water condensation in the exhaust stream, potentially forming a sulfuric acid (H_2SO_4) byproduct [38]. This byproduct can gather in the interior surface of the thrust reverser doors and nozzle, and eventually compromise the existing protective finish and generate surface corrosion [38].

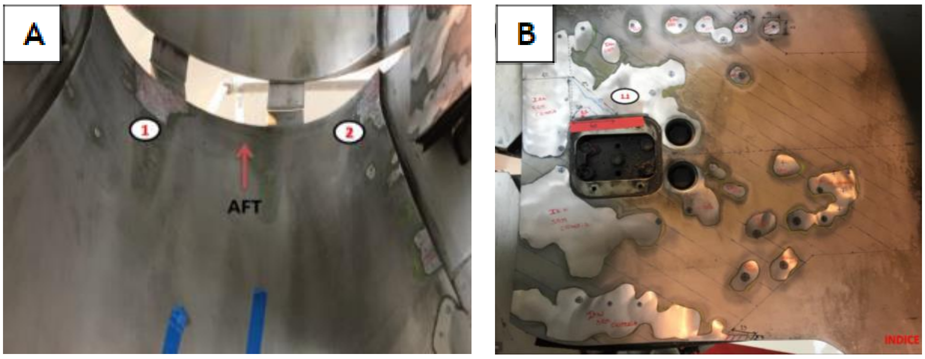

Figure 4.25: Falcon 2000ex Easy thrust reverser affected areas after corrosion removal (A – door; B – nozzle). (Images obtained from NetJets Europe portfolio)

To solve this problem, the manufacturer suggested the application of an improved epoxy-based coating, through the Service Bulletin No. 197 – R2: “Exhaust – Thrust Reverser – Nozzle and Doors Corrosion Repair”, which had been tested and shown benefits when compared with the original protective coating. When performing this SB, the corrosion is removed from the thrust reverser doors and nozzle interior surfaces, the old protective coating is removed, the surface cleaned, and the new protective coating is applied [38].

Although the application of the new protective coating should present improvements against the sulfuric acid byproduct, this is not what came to happen. Except for the aircraft #1, that accomplished the SB in 2014, all the other aircraft of the fleet performed the SB between 2010 and 2011 and, as we can see in Table 4.11. It is possible to conclude that the SB does not do the desired effect, with corrosion being frequently found in the same locations, after the accomplishment of the Service Bulletin. Although there is no correlation between the number of findings in each of the aircraft, the aircraft #4 and #7 show the highest number of findings (8) of the fleet, after SB accomplishment, and the aircraft #5 show the lowest number of findings (3) of the fleet, after SB completion.

Table 4.11: Timeline of thrust reverser corrosion findings in the Falcon 2000ex Easy fleet (green: start year of operation; orange: service bulletin accomplishment year).

YEAR / TAIL	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
A/C #1									1		2	1	2	1	1	8
A/C #2								1	2			1	2		2	8
A/C #3							1	2						2	3	8
A/C #4						3				2	1			1	4	11
A/C #5									1		1				1	3
A/C #6							2			2		1	2	1		8
A/C #7						1	1	2		2		3	1			10
A/C #8							1	2	1	3		2		1		10
A/C #9							1	1	1	1	1			2		7
A/C #10						2		2			2		3			9
Total						6	6	10	6	10	7	8	10	8	11	82

Economic and Operational Impact

The corrosion problem, found on the thrust reverser doors and nozzle, affects the entire NetJets Europe Falcon 2000ex Easy fleet. A total of 82 corrosion findings were found in the Falcon 2000ex Easy fleet, with 3 to 11 findings per aircraft.

The economic and operational impact related to maintenance of the thrust reversers is presented in Table 4.12. All the cost percentages presented are associated with either corrosion treatment or replacement of thrust reversers assemblies. Note that, due to the unavailability of data, discrepancies between aircraft may be found in the table.

From the available data, it is possible to observe that this problem represents 48.2% of the total corrosion costs of the fleet, being the biggest problem of the fleet, economically speaking. Most of this cost percentage is attributed to maintenance costs of the aircraft #2, representing 32.7% of the total fleet corrosion costs, with 1161 labor hours spent in the maintenance of corrosion damages. Within the total corrosion costs spent on this aircraft, this problem represents 67.8% of that total.

Table 4.12: Economic and operational impact of the thrust reverser corrosion problem (N/A: Not Available).

	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	A/C #8	A/C #9	A/C #10	Fleet
No. of Findings	8	8	8	11	3	8	10	10	7	9	82
Corrosion costs related to thrust reversers in relation with the total corrosion costs (respective aircraft)	29.3%	67.8%	N/A	48.3%	3.2%	15.3%	2.6%	1.6%	5.9%	N/A	-
Corrosion costs related to thrust reversers in relation with the total corrosion costs (fleet)	7.3%	32.7%	N/A	7.81%	0.2%	0.1%	0.02%	0.03%	0.01%	N/A	48.2%
Labor Hours	321.2	1161	N/A	141.6	15.6	10.6	N/A	N/A	N/A	N/A	1650.1

Proposed Measure

Since the protective coating suggested by the aircraft manufacturer was not as effective as expected, a new and more effective preventive measure had to be found.

In order to find an appropriate and improved protective coating, the case was presented to Av-DEC, a specialized company in aircraft corrosion prevention. After reviewing the case, Av-DEC recommended the application of an improved protective coating (Figure 4.26-A): Tuff Stuff™ (TS1228). A two-component polyurethane material, designed for use as a weather-tight, self-leveling, rigid sealant [39]. This coating is an injectable sealant (Figure 4.26-B), easy to remove and install, with excellent adhesion to itself after repair or inspection and provides a high degree of environmental protection with maximum sealing [39].

At the time of this revision, Av-DEC was already working with another operator, for the application of this product in a different type of aircraft, presenting the same problem. Tests were being conducted in the interior surface of the thrust reverser, in order to find the temperature of the exhaust stream when passing through this area, in two engine operating conditions: full power and idle.

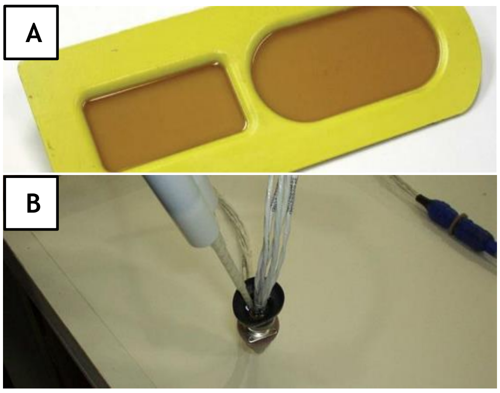

Figure 4.26: Recommended protective coating (A – TS1228 coating; B – application method) (adapted) [39].

The application of Av-DEC protective coating is the proposed measure for this case study, but before the product can be applied, the same tests will need to be conducted to find the exhaust stream temperature (temperature not mentioned in the aircraft or engine manuals), to verify if the coating withstands this operating temperature.

4.5.3.2 Horizontal Stabilizer Trailing Edge

The Falcon 2000ex Easy has a cruciform tail configuration (Figure 4.27), where the horizontal stabilizer intersects the vertical stabilizer somewhere near the middle, above the fuselage. Since this aircraft has two engines mounted on an aft-fuselage configuration, this tail configuration allows the horizontal stabilizer to avoid proximity to the jet exhaust, while providing undisturbed airflow to the lower part of the rudder (attached to the vertical stabilizer) during high angle of attack conditions and spins [40].

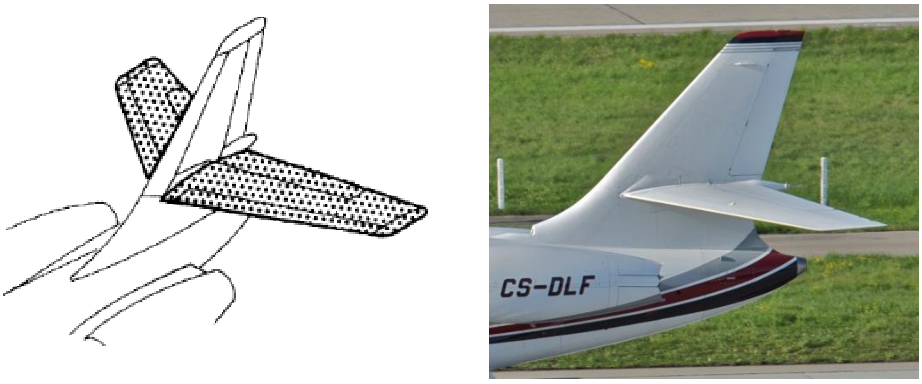

Figure 4.27: Falcon 2000ex Easy tail configuration [61, 62].

The horizontal stabilizer is a fixed surface, part of the aircraft empennage, essential to maintain the aircraft in longitudinal balance and provide longitudinal static stability. Also, to the horizontal stabilizer is attached a control surface, the elevator, which allows the aircraft nose to move up and down during flight [31].

Problem Breakdown

In this case study, corrosion was found in the trailing edge of the horizontal stabilizer, more specifically exfoliation corrosion (Figure 4.28). It is possible to see, in the image, the layered appearance, characteristic of this type of corrosion, due to the expanding corrosion products that force the metal away from the body of the material.

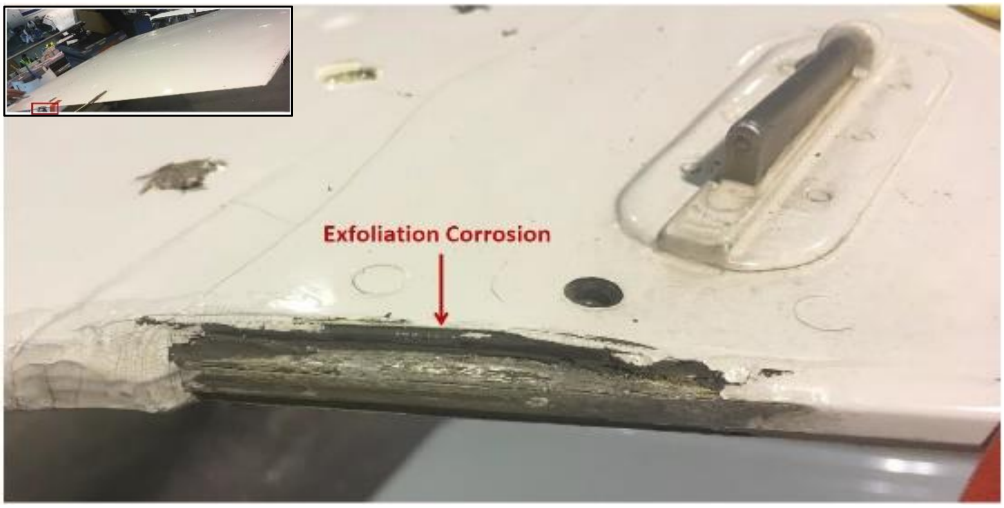

Figure 4.28: Exfoliation corrosion found in the horizontal stabilizer trailing edge. (Images obtained from NetJets Europe portfolio)

According to the aircraft manufacturer, the cause behind this problem is a condensation or water ingress in this area [41].

Economic and Operational Impact

The corrosion damage, in the trailing edge of the horizontal stabilizer, was found during the A+ (every 8 months) inspections, on 8 out of 10 aircraft, with a total of 17 findings[9] in the Falcon 2000ex Easy fleet.

It is possible to visualize in Table 4.13, the impact, both economic and operational, for the only aircraft with available information: aircraft #2. For this aircraft, the corrosion costs of this

[9] one corrosion finding corresponds to a corrosion damage found in only one of the horizontal stabilizers (left or right).

problem represent 6.14% of the total aircraft corrosion costs, having a significant amount of labor hours (263.9 hours), due to the replacement of both, left and right, horizontal stabilizers. In terms of fleet corrosion costs, this problem represents 2.96% of that total.

Table 4.13: Economic and operational impact of the horizontal stabilizer corrosion problem (N/A: Not Available).

	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #8	A/C #10	Fleet
No. of Findings	1	3	2	3	1	1	3	3	17
Corrosion costs related to horizontal stabilizer in relation with the total corrosion costs (respective aircraft)	N/A	6.14%	N/A	N/A	N/A	N/A	N/A	N/A	-
Corrosion costs related to horizontal stabilizer in relation with the total corrosion costs (fleet)	N/A	2.96%	N/A	N/A	N/A	N/A	N/A	N/A	2.96%
Labor Hours	N/A	263.9	N/A	N/A	N/A	N/A	N/A	N/A	263.9

Proposed Measure

This case study is the example of a gap found in the Falcon 2000ex Easy fleet CPCP, since a solution for this problem already existed, made available by the aircraft manufacturer.

In 2013, the aircraft manufacturer published the optional Service Bulletin No. 275 – "Improvement of Horizontal Stabilizer Trailing Edge Draining", which, at the time of this revision, had not been accomplished in any of the aircraft of the fleet.

When accomplishing this SB, the horizontal stabilizer trailing edge is inspected for corrosion and repaired, if necessary, and a drain hole (Figure 4.29) is added in the horizontal stabilizer lower panel [41]. The addition of this hole will improve water drainage in the horizontal stabilizer, allowing to avoid increased downtime and maintenance costs, due to repairs or replacements, in the future.

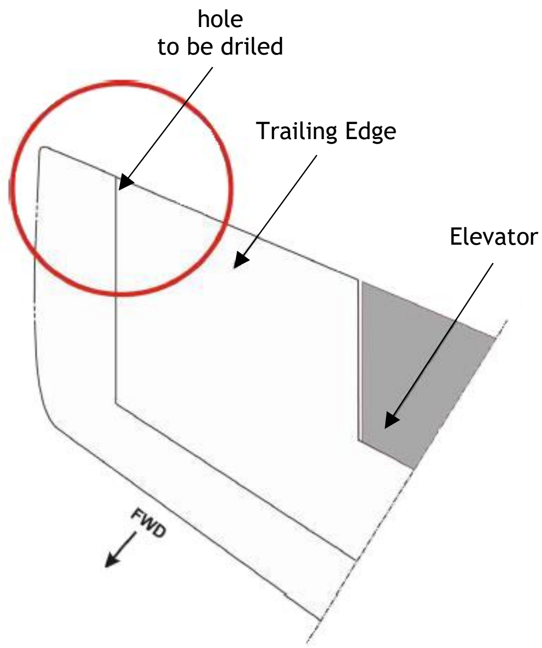

Figure 4.29: Improvement of the horizontal stabilizer drainage system, with the addition of a hole near the trailing edge [41].

4.5.3.3 Mechanical Servicing Compartment Floor Beam

The mechanical servicing compartment is located in the tail of the aircraft. Access to this compartment can be performed through a door (Figure 4.30) located in the left side of the aircraft tail.

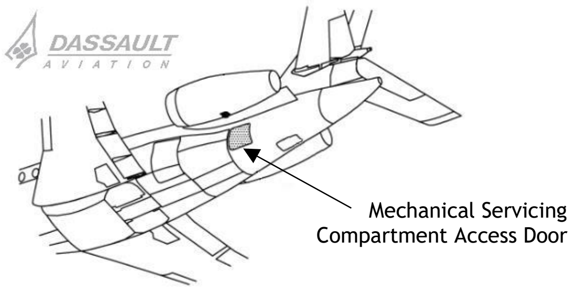

Figure 4.30: Falcon 2000ex Easy mechanical servicing compartment access door [60].

Problem Breakdown

Corrosion was found on the floor beam, located between the fuselage frames 30 and 32 (Figure 4.31), near the entrance of the mechanical servicing compartment, where the door and the stairs that give access to the compartment are attached.

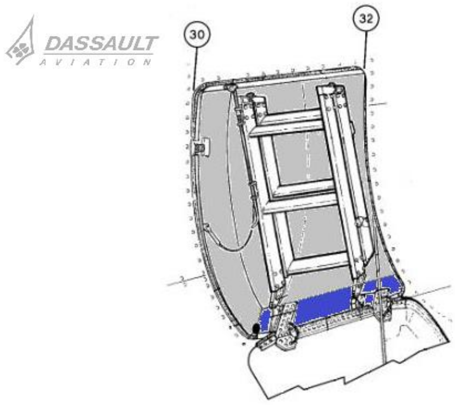

Figure 4.31: Location of the corroded compartment floor beam (in blue) (adapted) [60].

The corrosion found on the beam is light and superficial, with a light brown appearance (Figure 4.32). When detected, usually at the A+ (8 months) inspections, the corrective action usually involves corrosion removal, blending, surface cleaning, and re-protection of the affected areas (Figure 4.33).

Figure 4.32: Superficial corrosion (light brown areas) found in mechanical servicing compartment floor beam. (Image obtained from NetJets Europe portfolio)

Figure 4.33: Floor beam affected areas after corrosion removal. (Image obtained from NetJets Europe portfolio)

Economic and Operational Impact

This corrosion problem, found on the beam of the mechanical servicing compartment, affects 9 out of 10 NetJets Europe Falcon 2000ex Easy aircraft, which makes it a recurrent problem.

The economic and operational impact related to the maintenance of the floor beam corrosion damage is presented in Table 4.14. All the cost percentages presented are associated with corrosion treatment of the beam. Note that, due to the unavailability of data at the time of this revision, discrepancies between aircraft may be found in the table.

Table 4.14: Economic and operational impact of the floor beam corrosion problem (N/A: Not Available).

	A/C #1	A/C #2	A/C #3	A/C #4	A/C #5	A/C #6	A/C #7	A/C #8	A/C #9	Fleet
No. of Findings	1	1	1	1	2	1	2	2	2	13
Corrosion costs related to compartment beam in relation with the total corrosion costs (respective aircraft)	0.50%	5.19%	N/A	N/A	0.20%	N/A	1.32%	1.09%	N/A	-
Corrosion costs related to compartment beam in relation with the total corrosion costs (fleet)	0.12%	2.50%	N/A	N/A	0.01%	N/A	0.01%	0.02%	N/A	2.67%
Labor Hours	11	223.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	234.1

From the available data, it is possible to observe that was found a total of 13 corrosion findings in the Falcon 2000ex Easy fleet, with 1 to 2 findings per aircraft. In relation to maintenance costs associated to the beam corrosion damages, this problem represents 2.67% of the total corrosion costs of the fleet. Most of this cost percentage is attributed to the corrosion costs of the aircraft #2, representing 2.50% of the total fleet corrosion costs, with about 223 labor hours spent in maintenance.

Proposed Measure

No solution to this problem was available in aircraft manufacturer documentation at the time of this revision. To get around this problem, much like the problem found in the thrust reverser, the beam case was also presented to the corrosion prevention company, Av-DEC. After reviewing the case, Av-DEC recommended the use of one of two corrosion prevention tapes (Figure 4.34): TufSeal® (HT3000) or HI-TAK® Tape (HT3935-7).

The first is a pre-cured polyurethane tape sealant with a fiberglass carrier and polytetrafluoroethylene (PTFE) backing for one-sided sealing [42]. The second is also pre-cured polyurethane tape sealant but has a fiberglass carrier providing two-sided sealing [43].

Nevertheless, the two tapes were designed for sealing and moisture-proofing irregular surfaces, commonly used in this type of location (fuselage beams under floorboards) [42, 43]. Ease of installation and removal, these tapes are efficient in preventing corrosion development in the affected area.

Figure 4.34: Av-DEC corrosion prevention tapes (left: HT3000; right: HT3935-7) [42, 43].

Chapter 5

Summary

5.1 Conclusions

Due to an improvement in corrosion awareness over the years, the damages found nowadays, are less severe than the ones found in aircraft in the last century. This was possible due to a cooperation between OEMs, aircraft manufacturers, and operators. The OEMs and aircraft manufacturers started to invest more time developing improved corrosion resistant components and structures, and the operators developing good Corrosion Prevention and Control Programs. However, operators that implement CPCPs into the AMP, based on the aircraft manufacturer baseline program, may not have a program adjusted to their area of operation, which in turn may increase maintenance costs, while decreasing aircraft availability and the safety level.

The results found in this dissertation show that, operators that do not have a CPCP adequate to the area of operation, such as the case of NetJets Europe, need to perform periodic revisions of these programs, in order to adjust them to the reality faced by the aircraft operator or owner. With CPCP revisions, the operator can identify corrosion prone areas in each aircraft model and this way, learn from the experience obtained from the fleet operation. With this practice, it is possible to establish areas that should be given more attention, either through more inspections being performed, use of more effective protecting systems, etc.

In the NetJets Europe case, two fleet CPCPs were revised. One being the youngest and shorter of the two, the Global 6000 fleet, and the other the oldest and longest of the two, the Falcon 2000ex Easy fleet. To help identify the critical areas with recurrent corrosion damages, and high economic and operational impacts, a database was developed for each fleet, with all the corrosion damages found since the beginning of operation.

From the database results, was possible to confirm that the number of corrosion findings, and associated maintenance costs and labor hours, are the highest in aging fleets, such as the case of the Falcon 2000ex Easy fleet.

In the Global 6000 fleet, the wings and flight controls were identified as the areas most prone to corrosion. In turn, wings, landing gear, and fuselage areas were identified as susceptible to corrosion in the Falcon 2000ex Easy fleet.

With complementary economic and operational impact studies, in terms of maintenance costs and downtime respectively, was possible to identify specific component or structural corrosion problems, that needed to be further investigated with full root cause analyses. For the Global 6000 fleet, the flap tracks, nose landing gear, and passenger door actuator chain problems were analyzed, while in the Falcon 2000ex Easy fleet, the cases of thrust reversers, horizontal stabilizer trailing edge and mechanical servicing compartment floor beam, were selected for analysis.

Performing root cause analyses, was possible to identify the cause of corrosion for most cases and have a better assessment of the problem, allowing to find the best countermeasures to prevent corrosion reoccurrence. Among the countermeasures proposed are: changes in MPD task intervals (such as the task interval change for inspection of flap tracks in the Global 6000 fleet), introduction of procedures in existent MPD tasks (such as the addition, to existing tasks, of the procedures for lubrication of the passenger door actuator chain, and inspection of the NLG sealants in the Global 6000 fleet), use of improved and more resistant protecting systems (such as the cases of the Falcon 2000ex Easy thrust reversers coating protection and floor beam corrosion resistant tape), accomplishment of aircraft manufacturer modifications, for example service bulletins (such as the accomplishment of the SB for addition of a drain hole to the Falcon 2000ex Easy horizontal stabilizer). For more effective corrosion prevention, it is possible to use a combination of these types of countermeasures, not being limited to a single one by case. Also, any of these countermeasures can be implemented to other fleets, presenting similar problems.

These corrosion preventive measures can potentially improve safety and reduce maintenance costs and downtime. Due to major economic implications, reducing downtime is vital to commercial success, especially for a business jet operator, such as NetJets Europe, since it allows to have a higher aircraft availability.

Finally, is important to refer that, due to a time-consuming task of searching and organizing corrosion findings, in order to create a database, less time was available for analyzing the data and perform root cause analyses of corrosion problems. With this in mind, operators that have well-established and maintained corrosion findings databases, will provide the personnel in charge of the CPCP revisions, with more time to focus on more important tasks, such as those mentioned before.

5.2 Future Work

In the future, the measures proposed in this dissertation should be evaluated, in order to study the impact in maintenance costs and labor hours.

Since this work only “scratched” the surface, in terms of corrosion problems with room for improvement (especially in the Falcon 2000ex Easy fleet), more root cause analyses could be performed in future works. The methodology presented could also be performed in other fleets, to evaluate the respective CPCP.

The same study of CPCP evaluation could be performed categorizing the findings with the corrosion levels presented in Chapter 3. While findings categorized with corrosion level 1 should be accepted, findings with corrosion levels 2 and 3 should be further analyzed with root cause analyses, to better understand the problem and apply the appropriate measures.

In order to reduce the time-consuming task of collecting data, used to perform the type of study presented in this dissertation, a dedicated corrosion findings database could be created, with data entry such as tail, finding date and description, corrective action, maintenance costs and labor hours. Another possibility is the addition of a label, when entering data to existing operator’s databases. This corrosion data could later be reached through filter options in the databases.

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Annex A

Corrosion Severity Maps

A.1 FAA Europe and Minor Asia Corrosion Severity Map (1991)

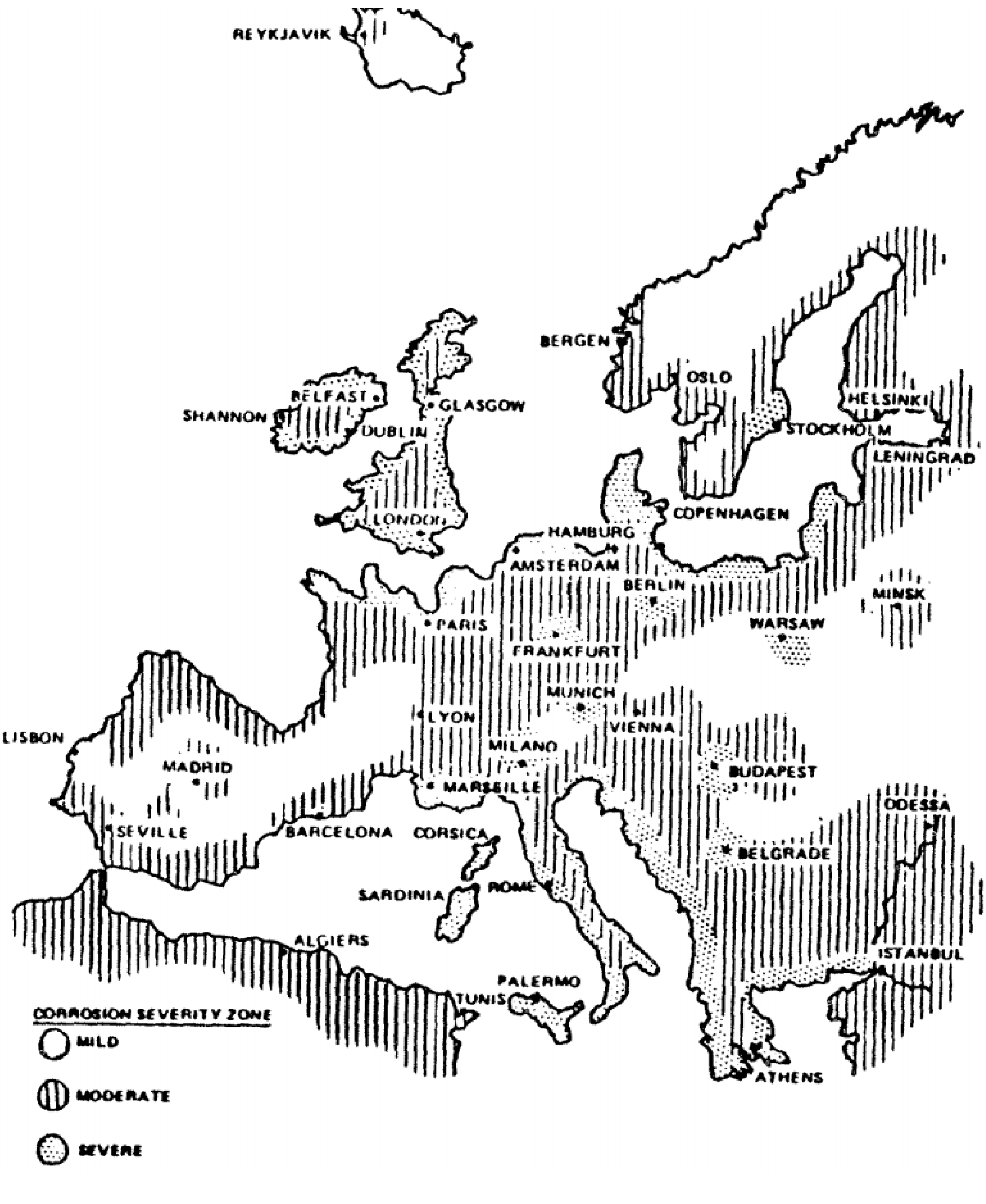

Figure A.1: FAA Europe and minor Asia corrosion severity map [25].

A.2 Cessna Europe and Minor Asia Corrosion Severity Map (2013)

Figure A.2: Cessna Europe and minor Asia corrosion severity map [63].

Annex B

Galvanic Series

Corroded end (anodic)	
Magnesium	Muntz metal
Magnesium alloys	Naval bronze
Zinc	Nickel (active)
Galvanized steel	Inconel (active)
Aluminum 6053	Hastelloy C (active)
Aluminum 3003	Yellow brass
Aluminum 2024	Admiralty brass
Aluminum	Aluminum bronze
Alclad	Red brass
Cadmium	Copper
Mild steel	Silicon bronze
Wrought iron	70/30 Cupro-nickel
Cast iron	Nickel (passive)
Ni-resist	Iconel (passive)
13% Chromium stainless steel (active)	Monel
50/50 Lead tin solder	18-8 Stainless steel type 304 (passive)
Ferretic stainless steel 400 series	18-8-3 Stainless steel type 316 (passive)
18-8 Stainless steel type 304 (active)	Silver
18-8-3 Stainless steel type 316 (active)	Graphite
Lead	Gold
Tin	Platinum
	Protected end (cathodic)

Figure B.1: Galvanic series for metals and alloys [7].

Annex C

General Corrosion Maintenance Procedure

The general maintenance procedure for corrosion inspection and repair usually involves the following tasks [44]:

1. Gain access to the structure or component to be inspected
2. Clean to remove surface contaminants
3. Stripping of protective coatings
4. Inspection to detect corrosion or corrosion related damage
5. Documentation of inspection results
6. Repair or treatment of corrosion damage
   6.1 Maintenance requests and planning for corrosion correction:
      a. Corrosion removal
      b. Sheet metal or machinist work
      c. Replacement of part
7. Application of surface treatment (Alodine, etc.)
8. Application of cathodic protection systems (for example, zinc)
9. Close access performed in 1.
10. Preparation and cleanup activities associated with activities 1–9;