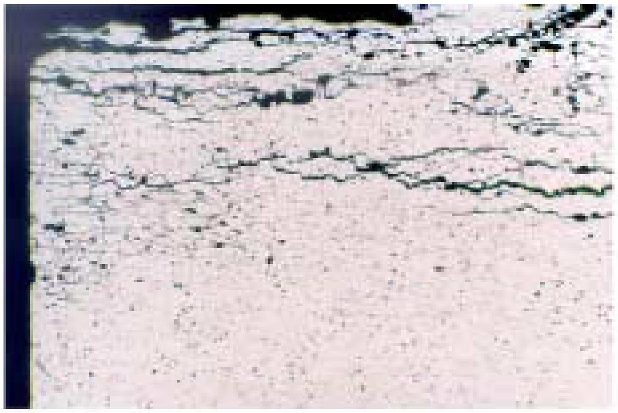
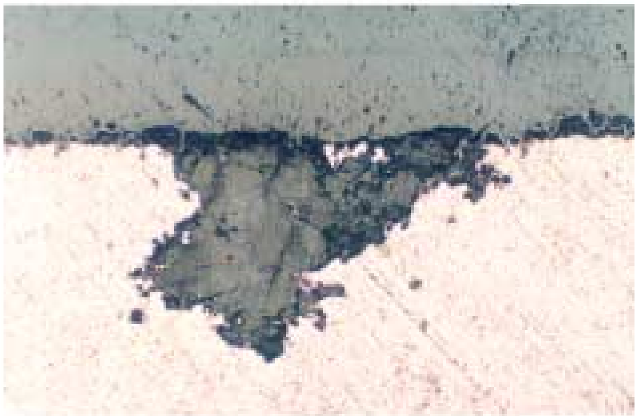
APPENDIX P

AIRCRAFT



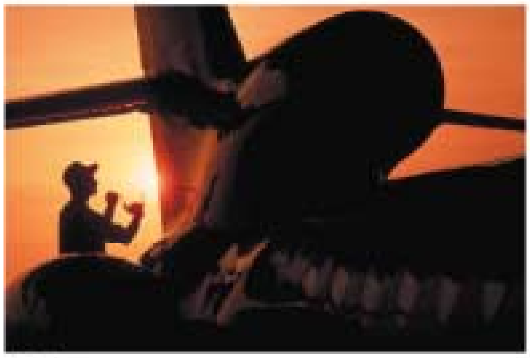
Exfolation corrosion in aircraft structural member



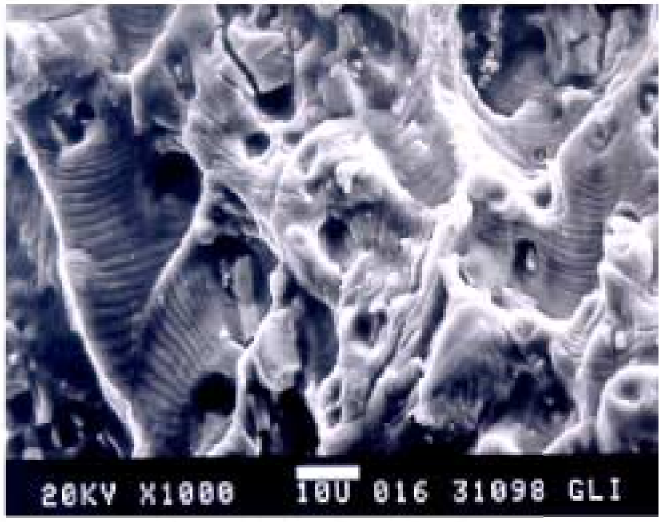
Pitting in aluminum

Aircraft aluminum corrosion

Wing repair



Maintenance



SEM photo of corrosion fatigue of aluminum alloy

AIRCRAFT

GERHARDUS H. KOCH, PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

In 1998, the combined aircraft fleet operated by U.S. airlines was more than 7,000, of which approximately 4,000 were turbojets. At the start of the "jet age" (1950s-1960s), little or no attention was paid to corrosion and corrosion control. These aircraft are characterized by a design that primarily addressed strength and fail-safe criteria. Aircraft from this era that are still in use include the B-707, DC-8, DC-9, B-727, L-1011, DC-10, and the earlier models of the B-737 and B-747. The second generation of jet aircraft built in the 1970s and 1980s incorporated some corrosion control; however, major emphasis was placed on the incorporation of damage tolerance standards into the design. This generation of aircraft includes the B-737 (-300, -400, and -500); B-747-400; B-757; B-767; MD-81, -82, and –83; MD-88; MD-11; and F-100. As part of the durability standards, airframe manufacturers started to use corrosion-inhibiting primers and sealants. Moreover, the Federal Aviation Administration (FAA) issued Airworthiness Directives (ADs) related to corrosion control in design and maintenance.

The third generation of jet transport aircraft includes the B-777 and the new generation B-737 (-600, -700, and -800). In addition to the key characteristics of the first- and second-generation aircraft, the third-generation aircraft are characterized by the incorporation of significant improvements in corrosion prevention and corrosion control in design.

The total annual (1996) cost of corrosion for the U.S. aircraft industry was estimated at $2.225 billion, which includes the cost of design and manufacturing at $0.225 billion, corrosion maintenance at $1.7 billion, and downtime due to corrosion at $0.3 billion. With the availability of new corrosion-resistant materials and an increased awareness of the impact of corrosion on the integrity and operation of jet aircraft, the current design life of 20 years can be extended without jeopardizing structural integrity and significantly increasing the cost of operations.

Opportunities for Improvement and Barriers to Progress

One of the major concerns of the aircraft and airline industry is the aging of several types of aircraft beyond the design life of 20 years. This aging of the fleet has been the subject of considerable attention by the industry and the government for many years, and has resulted in increased maintenance efforts on the aging aircraft. In April 1988, the sudden decompression of an Aloha Airline B-737-200 airplane and the subsequent separation of the fuselage skin resulted in more focused attention on the problems associated with aging aircraft.

In order to prevent similar incidents on other airplanes, manufacturers, airline operators, and other aviation industry representatives formed the Airworthiness Assurance Working Group to develop all measures considered necessary to ensure the continued safety of aging aircraft. Individual working groups for each aging aircraft model were directed to develop Corrosion Prevention and Control Programs (CPCPs). The recommendations developed in the CPCPs were incorporated in the mandatory Airworthiness Directives (ADs) issued by the FAA. These ADs

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define a baseline program for each aircraft model, establishing minimum requirements for airline operators to prevent or control corrosion that may jeopardize continuing airworthiness.

Significant improvements have been made in the corrosion design and manufacturing of new airplanes. Aircraft manufacturers have implemented many key design improvements over the past 25 years, ranging from the use of more corrosion-resistant materials, to improved adhesive bonding processes, to the use of sealants in fastener holes and on faying surfaces, to the control of spillage of galley and lavatory fluids. Because of the significance in the corrosion design and manufacturing of aircraft, the design service life of new generation aircraft was moved from 20 to 40 years. Despite these improvements, several concerns remain that impede progress in effective corrosion control. Although state-of-the-art materials are available, there appears to be a reluctance to incorporate them into new designs. For example, the corrosion- and stress corrosion cracking-prone aluminum alloys 7075-T6 and 2024-T3 are still widely used despite the availability of new corrosion-resistant aluminum alloys with equal strength and fatigue properties.

A major problem is the corrosion maintenance of the aging aircraft fleet. Although it was stated by a major domestic U.S. airline that . . . *"the degree to which an airline aggressively pursues corrosion prevention from the beginning of an airplane's maintenance life is the single most important measure affecting future maintenance costs,"* corrosion maintenance is often not performed adequately. Traditionally, corrosion has not been given sufficient attention with respect to structural integrity. This may have been due to the lack of understanding of the corrosion process and the inability to predict the nucleation and growth behavior of corrosion. Corrosion has therefore not been incorporated in the damage tolerance assessments, and an approach of "find it and fix it" has generally been accepted. This approach leads to extensive corrosion of both structural and non-structural parts, which significantly increases the cost of maintenance. Moreover, as airframes continue to age, corrosion will increasingly affect the structural integrity of these airframes.

Furthermore, state-of-the-art corrosion control techniques that are available are often not applied to older aircraft because of regulation, lack of awareness, education, and technology transfer.

Recommendations and Implementation Strategy

For many years, the importance of corrosion and corrosion control has been underestimated, and a "find it and fix it" approach to corrosion maintenance has generally prevailed. It must be understood that if corrosion is not taken care of in a timely manner, an airplane, as an important asset and with regard to its structural integrity, will be threatened. While it is the responsibility of the airframe manufactures to implement the newest available technology to mitigate corrosion, the operators must have a corrosion control program in place throughout the life of the airplane. The "find it and fix it" approach must be replaced by a more fundamental approach that is based on an understanding of the corrosion process and the ability to predict and monitor its behavior.

Corrosion prediction models need to be developed in order to define a cost-effective corrosion integrity program. In addition, development of improved inspection and monitoring techniques is needed to expand the capabilities in order to detect and monitor flaws from an early stage.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Implement corrosion control programs early in the life of the airplane. Consciousness should be present at the design phase at all operator levels – from maintenance technicians to upper management.
Change perception that nothing can be done about corrosion.	The industry is well aware of the corrosion problems, but needs to put in more effort to do something about it.
Advance design practice to realize corrosion cost-savings.	The newest generation of airplanes has increased their design service life from 20 years to 40 years by incorporating corrosion control in the design. Research and development for corrosion-resistant materials and corrosion control methods need to continue.
Change technical practices to realize corrosion cost-savings.	Incorporation of state-of-the-art inspection and monitoring techniques in a corrosion management strategy will be key.
Change policies and management practices to realize corrosion cost-savings.	The "find it and fix it" approach should be amended by a prevention and control approach.
Advance life prediction and performance assessment methods.	The development of corrosion life prediction and performance models is critical to cost-effective structural integrity management. Effective predictive models are currently not available.
Advance technology (research, development, and implementation).	The needed technology advances include a better understanding of the corrosion process in aircraft materials and improved inspection and monitoring techniques.
Improve education and training for corrosion control.	Provide education to design and maintenance personnel in order to gain a better understanding of corrosion and be cognizant of current corrosion-resistant materials and corrosion control techniques. Training courses for maintenance technicians are necessary if effective corrosion maintenance is desired.

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SECTOR DESCRIPTION

Background

According to data presented in the 1999 edition of the *Aviation & Aerospace Almanac*, the combined aircraft fleet operated by U.S. airlines in 1998 totaled 7,478.(1) These include fixed-wing turboprop and turbojet, and rotary wing aircraft. Of this total number of aircraft, 3,973 are turbojet aircraft, which are divided into 29 different types for domestic and international service. Table 1 shows a 1997 listing of the major U.S. carrier fleets with the number and average age of the fleets' airplanes.(1)

Table 1. Major carrier jet fleets in 1997, as reported in the *Aviation & Aerospace Almanac*.(1)

CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE
ALASKA			**DELTA (cont.)**			**UNITED**		
B-737	31	6.9	L-1011	53	17.7	A-319*		
MD-80	44	7.7	MD-11	12	4.0	A-320	35	2.1
Total	**75**	**7.4**	MD-80	119	6.4	B-727	74	17.7
AMERICA WEST			MD-90	12	1.4	B-737	225	11.9
A-320	25	5.6	**Total**	**538**	**11.7**	B-747	56	14.1
B-737	61	12.0	**FEDERAL EXPRESS**			B-757	92	4.8
B-757	14	10.0	A-300-600	19	1.5	B-767	42	8.8
Total	**100**	**10.1**	A-310	29	12.7	B-777	16	1.4
AMERICAN			B-727	159	22.5	DC-10	52	21.4
A-300-600	35	7.2	B-747	2	19.6	**Total**	**592**	**11.5**
B-727	81	19.7	DC-10	34	17.1	**UNITED PARCEL SERVICE**		
B-757	90	4.7	MD-11	21	3.6	B-727	53	27.8
B-767	71	7.9	**Total**	**264**	**17.7**	B-747	16	24.1
DC-10	35	22.2	**NORTHWEST**			B-757	57	4.5
F-100	75	3.8	A-320	50	5.1	B-767	9	0.7
MD-11	16	4.4	A-330			DC-8	9	28.0
MD-80	260	8.6	B-727	46	17.8	**Total**	**144**	**16.5**
Total	**663**	**9.4**	B-747	43	15.5	**U.S. AIR**		
CONTINENTAL			B-757	48	7.2	B-737	203	10.4
A-300	4	16.2	DC-9	180	26.3	B-757	34	6.2
B-727	30	20.5	DC-10	37	22.5	B-767	11	7.5
B-737	132	11.5	MD-80	8	15.1	BAE-146	4	11.3
B-757	71	1.8	**Total**	**412**	**18.9**	DC-9	72	23.7
B-777*			**TWA**			F-100	40	5.8
DC-9	28	24.3	A-330*			F-28	13	12.1
DC-10	18	20.1	B-727	47	24.1	MD-80	31	14.7
MD-80	67	11.9	B-747	15	25.8	**Total**	**408**	**12.3**
Total	**350**	**11.9**	B-757	1	0.3	**SOUTHWEST**		
DELTA			B-767	14	12.4	B-737	241	8.1
B-727	129	19.7	DC-9	58	25.6	**Total**	**241**	**8.1**
B-737	67	11.8	L-1011	13	22.6			
B-757	88	7.9	MD-80	52	9.7			
B-767	58	8.3	**Total**	**200**	**19.9**			

Source: GKMG Consulting Services, Inc. **Data not available.*

The table shows that several types of airplanes are currently operating beyond the typical design life of 20 years. This aging of the commercial fleet has been the subject of considerable attention by industry and government for many years and has resulted in increased maintenance efforts for the aging aircraft. In April 1988, the sudden decompression of an Aloha Airline B-737-200 airplane and the subsequent separation of its fuselage skin [see the 1988 National Transportation Safety Board (NTSB) report](2) has resulted in more focused attention on the issue of aging aircraft. Although this incident was primarily attributed to widespread fatigue damage (WFD), the NTSB report addressed all factors that contributed to the structural deterioration of the airframe, including corrosion.

In order to prevent similar accidents in future airplanes, manufacturers, operators, and other aviation industry representatives joined together in September 1988 to form an Aging Aircraft Task Force Steering Committee (later called the Airworthiness Assurance Working Group).(3-5) Its charter was to develop all measures considered necessary to ensure the continued safety of aging airplanes. In order to accomplish this, the Airworthiness Assurance Working Group sponsored an industry-wide Structures Task Group for each aging airplane model. These included the following airplanes: Airbus A300; Boeing 707/720, 727, 737, and 747; British Aerospace BA1-11; Douglas DC-8, DC-9/MD-80, and DC-10; Fokker F-28; and Lockheed L-1011. Each group reviewed the various corrosion control practices with the primary objectives of maintaining airworthiness in an economical manner and establishing minimum procedures for preventing or controlling corrosion.

The working groups were directed to develop Corrosion Prevention and Control Programs (CPCPs). The recommendations developed in the CPCPs were incorporated in the Airworthiness Directives (ADs) issued by the Federal Aviation Administration (FAA). These ADs defined a baseline program for each airplane model, establishing minimum requirements for airline operators to prevent or control corrosion that may jeopardize continuing airworthiness. The baseline program includes definitions of corrosion, program implementation requirements, and mandatory reporting systems.

The mandatory CPCPs were intended to supplement each operator’s existing maintenance program. The corrosion programs are self-adjusting in that findings of unacceptable corrosion levels require operators to adjust the tasks. These maintenance program adjustments should preclude recurrence of unacceptable corrosion findings. The adjustments may include actions such as reduced repetitive task intervals and/or improved corrosion treatments. The anticipated cost per individual airplane to comply with the mandatory CPCPs was calculated in 1992 by the FAA prior to issuance of the ADs and is shown in table 2.(5) The table shows the annual cost per aircraft type based on a 6-year major overhaul cycle.

Table 2. Annual estimated cost (1992) to implement corrosion airworthiness directives for an individual airplane.(5)

MODEL	AD NUMBER	COST (IN $) (Based on a 6-Year Cycle)	U.S. AD FLEET SIZE AFFECTED
A-300	94-18-02	44,000	54
BAC-1-11	93-02-14	38,500	45
B-707/-720	90-25-07	80,640	74
B-727	90-25-03	80,000	1,143
B-737	90-25-01	38,720	232
B-747	90-25-05	188,800	65
DC-8	92-22-07	105,700	222
DC-9/MD-80	92-22-08R1	87,100	1,016
DC-10	92-22-09R1	51,900	244
F-27	94-15-11	28,880	55
F-28	94-05-02	29,600 (based on a 4-year cycle)	46
L-1011	93-20-03 95-21-07	139,700 14,000	117

Corrosion Modes

Corrosion in an aircraft manifests itself in several different forms. Pitting and crevice corrosion are the most common forms of corrosion in the 2000 and 7000 series aluminum alloys, which are the principle materials of construction. Pitting corrosion produces deterioration of the airframe structures in localized areas and can have high penetration rates. Pits often create stress concentrations, which may reduce the fatigue life of a component. Crevice corrosion, by itself, is more destructive than pitting corrosion. Crevice corrosion occurs when a corrosive fluid enters and is trapped between two surfaces, such as a joint, a delaminated bondline, or under a coating. Both pitting and crevice corrosion, when unchecked, can readily develop into exfoliation corrosion or intergranular stress corrosion cracking. Exfoliation corrosion is a form of intergranular corrosion where corrosion attack occurs along the grain boundaries of elongated grains, causing a leaf-like separation of the metal grain structure (see figure 1). This form of corrosion often initiates at unprotected end grains, such as at fastener holes and plate edges.

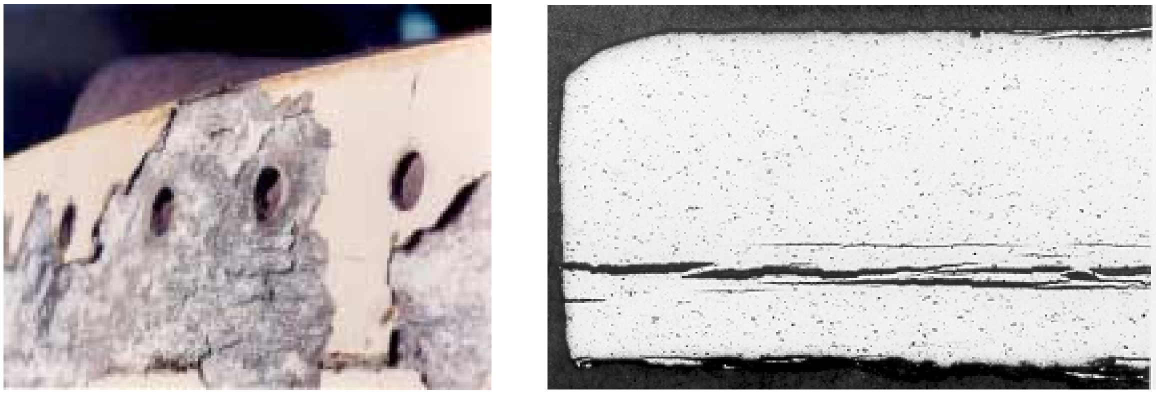

Figure 1. Exfoliation corrosion around fastener holes in aluminum alloy 7075-T6 fuselage section.

Intergranular stress corrosion cracking occurs when stresses are applied perpendicular to the susceptible grain boundaries. More so than pitting and crevice corrosion, susceptibility to exfoliation corrosion and intergranular stress corrosion cracking depends on alloy type, heat treatment, and grain orientation. Other common forms of corrosion include fretting corrosion, which occurs when two surfaces rub at high frequency and low amplitude in the presence of a corrosive environment, and galvanic corrosion, where dissimilar metals such as aluminum and steel are in direct contact. Isolating the different metals, which can be accomplished by proper design and assembly, can prevent both forms of corrosion.

Corrosion Causes

There are many contributing causes of corrosion in commercial aircraft.(6-7) Figure 2 shows some of the typical causes and sources of corrosion, which are divided into the two main categories of manufacturer and operator. The first potential source of corrosion is in the basic design process. Material selection, finishes, and structural configuration can have a significant impact on the corrosion performance of an airplane. During the design phase, attention must be paid to the basic principles of corrosion-conscious design, such as the selection of corrosion-resistant materials, the avoidance of dissimilar metal contact, crevices, stresses, and poor drainage. In addition, the selection of sealants and finish systems is an important part of a corrosion-conscious design. For example, the use of corrosion-inhibiting primers and sealants on fasteners and faying surfaces has become common practice for new airplanes, and the elimination of crevices is now required by “faying surface sealing” of all joints that are prone to corrosion. Corrosion-inhibiting compounds are routinely applied in the final assembly of many aircraft components, such as the inside fuselage crown and lower lobe, pressure bulkheads, pressure deck, under lavatories and galleys, wheel wells, wing-empennage cove areas, dry bays, empennage torque box interiors, and under fairings.

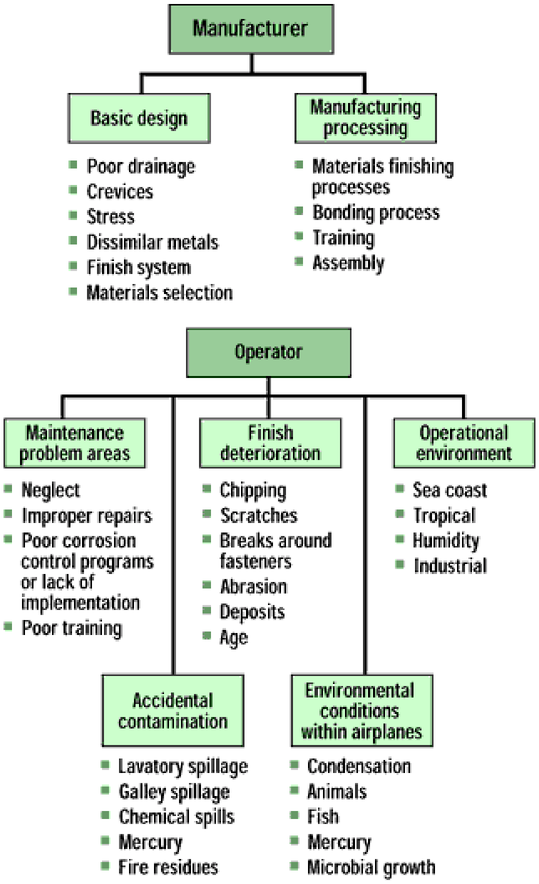

Figure 2. Typical causes and sources of corrosion.(7)

Another potential source of corrosion problems is in the manufacturing process. Specifically, the assembly and finishing processes can determine whether a specific component will be subject to premature corrosion. Of particular importance is the proper surface pretreatment and application of protective coatings and sealants, which must offer long-term durability in order to provide adequate corrosion protection.

Once airplanes are in the hands of operators, many factors, including operating conditions and maintenance practices, determine the corrosion performance of the airplanes. Operational environments such as marine, tropical, high humidity, and industrial can be extremely corrosive to the outside of an aircraft. Furthermore, during operation, the protective surface finishes can deteriorate by chipping, scratching, breaking around fasteners, abrasion, and aging. Environmental conditions inside an airplane can be even more damaging. For example, lavatory spillage, galley spillage, chemical spills, animal waste, microbial growth, fire residue, and corrosive cargo such as fish (saltwater) can create extremely corrosive conditions inside an airplane. Condensation that forms on the inside of the fuselage is also a potential source of internal corrosion. Boeing(8) has conducted an inspection of airplanes with the most severe moisture problems and found that as a result of moisture uptake in insulation blankets in B-737-300 airplanes, the weight had increased by an average of 36 kg (79 lb).

CORROSION CONTROL METHODS

Corrosion control can be accomplished in the design and manufacturing phase as well as in the operation and maintenance phase of the airplane.

Design and Manufacturing

Proper design for corrosion control must include the selection of materials, coatings, sealants, and corrosion-inhibiting compounds. In addition, consideration must be given to the avoidance of dissimilar metal contacts, access for maintenance, and proper drainage.

Material Selection

High-strength aluminum alloys are the most widely used airplane material because of their high strength-to-weight ratio. However, these alloys and the low-alloy, high-strength carbon steels are the two groups of airplane materials that are most susceptible to corrosion. Clad aluminum alloy sheets and plates are used where weight and function permit, while corrosion-resistant alloys and tempers are used to increase the resistance of the alloys to exfoliation corrosion and stress corrosion cracking. For example, the aluminum alloy 7055-T7751 plate, which is not susceptible to exfoliation corrosion, has replaced the alloy 7150-T651 plate on upper wing skins. Major structural forgings of aluminum alloys and steel may be shot-peened to improve their fatigue and stress corrosion life. Titanium alloys such as Ti-6Al-4V are used in severe environments, such as floor structures under entryways, galleys, and lavatories. Stainless steels are used where possible; however, a number of highly loaded structural components such as landing gears and flap tracks have to be made of low-alloy, high-strength steel. Fiber-reinforced plastics, which find wider application, are corrosion-resistant, whereas carbon fiber-reinforced plastics (CFRP) can induce galvanic corrosion in attached aluminum structures. An example of an application of CFRP is the Boeing 777 CFRP floor beam design where an aluminum splice channel is used to avoid attaching the floor beam directly to the primary structural frame (see figure 3).(7)

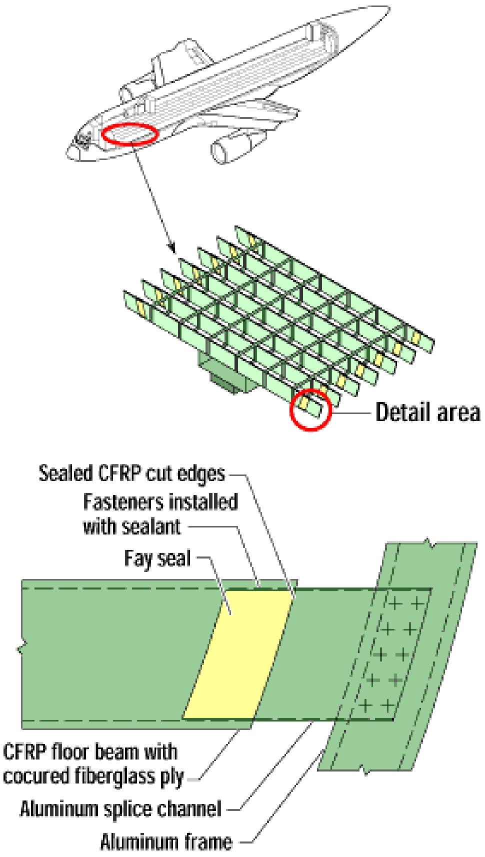

Figure 3. Boeing 777 design incorporating carbon fiber-reinforced plastic.(7)

Coating Selection

The most practical and effective means of protecting against corrosion is in the application of appropriate coatings. The coating system for aluminum alloys usually consists of an appropriate surface, such as an anodized surface with a corrosion-inhibiting primer. A commonly used process for anodization is phosphoric acid anodizing. The morphology of this film is such that primer adheres well. The corrosion-inhibiting primers that are generally used include Skydrol-resistant epoxies formulated for general use, resistance to fuel and hydraulic fluids, or for use on exterior aerodynamic surfaces. Exterior surfaces of the fuselage and vertical stabilizer are painted with a Skydrol-resistant, decorative polyurethane topcoat over a urethane-compatible epoxy primer that resists filiform corrosion. Titanium and stainless steel are cadmium plated and primed if they are attached to aluminum or steel parts. This is done in order to prevent galvanic corrosion of the aluminum or the steel.

Drainage

Effective drainage of the entire airplane structure is important in preventing fluids from becoming trapped in crevices. The entire lower pressurized fuselage is drained by a system of valved drain holes. The fluids are directed to these drain holes by a system of longitudinal and cross-drain paths through the stringers and frame shear clips. Figure 4 shows examples of improvements made in drainage.(7)

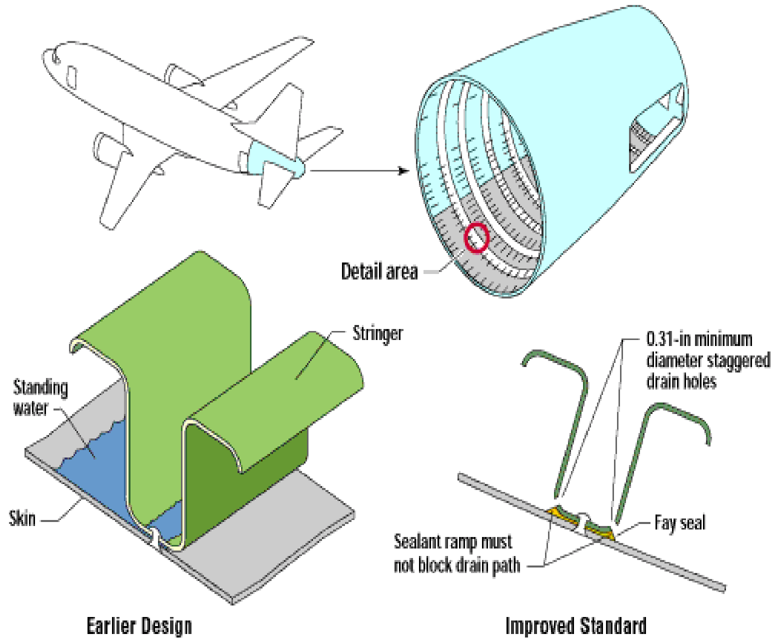

Figure 4(a). Lower lobe frame shear-tie drainage.

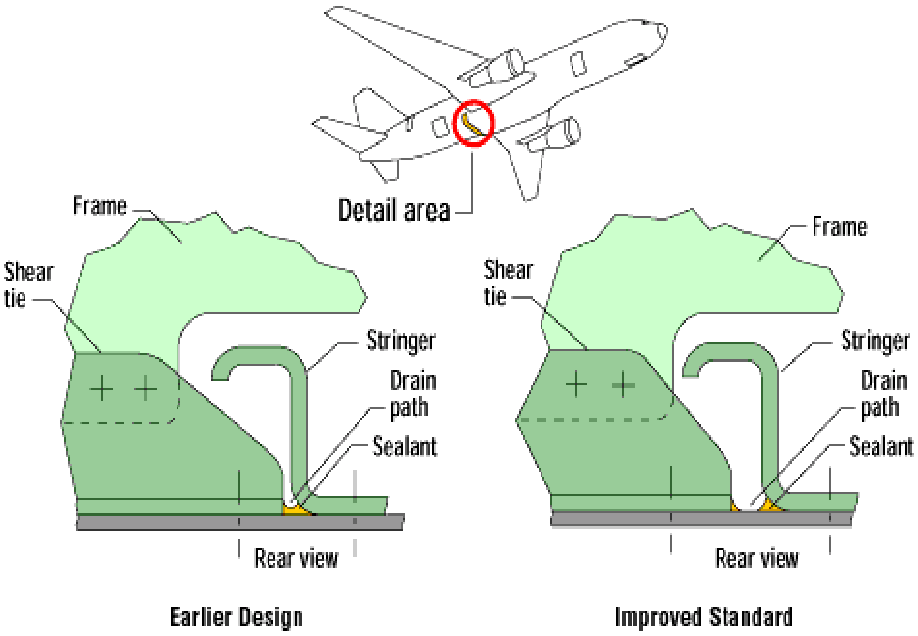

Figure 4(b). Lower lobe stringer drainage and sealing.[7]

Sealants

The potential for lap joint or joint crevice corrosion is eliminated by applying a sealant to the faying surfaces of the joints. A polysulfide sealant is typically applied to such areas as skin-to-stringer and skin-to-shear tie joints in the lower lobe of the fuselage, longitudinal and circumferential skin splices, skin doublers, the spar web-to-chord and chord-to-skin joints of the wing and empennage, wheel well structure, and pressure bulkheads. High-strength steel and titanium fasteners on the exterior of the airplane and fasteners that penetrate the pressurized portion of the fuselage are installed with a sealant. Finally, fillet seals are used in severe corrosion environments.

Corrosion-Inhibiting Compounds

Although the previously discussed design aspects provide most of the corrosion protection for airplanes, corrosion-inhibiting compounds (CICs) are widely used to provide additional protection, particularly when periodically applied in service. Typically, CICs are initially applied in areas that are prone to corrosion, such as in the lower lobe of the fuselage. In current production, CICs are applied to most aluminum structures. CICs are petroleum-based compounds that serve to displace water or serve as a coating. The water-displacing CICs are sprayed onto a structure to penetrate faying surfaces and keep water away from crevices. These CICs must be reapplied every few years to remain active, depending on the environment in which the airplane has been operating. The more viscous heavy-duty CICs are sprayed on as well, but they form a much thicker film and have less penetrating ability. They are used on parts of the airplane that are most prone to corrosion.

Access for Maintenance

The new generation aircraft are designed to provide easy access for frequent maintenance and corrosion inspections.

Operation and Maintenance

Design features and protective finishes applied during manufacturing and by operators after delivery of an aircraft should ensure a safe and economical service life; however, the aircraft requires continuous and appropriate maintenance by the operator to minimize corrosion. A proper corrosion maintenance program should prevent or eliminate conditions that can cause corrosion. These conditions include:

- trapped moisture,
- wet insulation blankets,
- plugged drain holes and passages,
- chipped or missing paint,
- loss of protective finish, and
- corrosive cargo.

Much corrosion can be avoided by proper and timely application of sealants and CICs. Particularly when components such as lavatories and galleys are removed for maintenance or repair, close attention should be paid to the proper sealant application procedures when these components are replaced. Moreover, maintenance programs should be able to detect corrosion at an early stage so that expensive repairs and replacement can be avoided. Nondestructive inspection (NDI) techniques that are being utilized include ultrasonic testing, eddy current testing, optical testing, and radiography. When corrosion is detected, it is removed by blending it out. When cumulative blend-out has reached an allowable limit (10 percent of the total thickness), the section or part will be replaced. Currently, there are efforts underway to further refine existing NDI techniques and to develop new techniques to be able to detect smaller flaws, as well as flaws and corrosion that are hidden within the structure and cannot be readily detected with current NDI techniques. Until recently, corrosion control of airplanes was based on the principle of "find and fix." However, even if all corrosion can be found, it cannot be completely eliminated. Thus, in an effort to control corrosion in an economical manner, corrosion is now being managed by a combination of selective blend-out and application of corrosion-preventive or water-displacing compounds.

CORROSION MANAGEMENT METHODS

Fleet Definition

The current operating fleet can be divided into three generations. The first generation are jet transport airplanes that were designed in the 1950s and 1960s where some of these are still in operation. These airplanes include the B-707, DC-8, DC-9, B-727, L-1011, and the earlier production models of the B-737 (-100, -200), B-747 (-100, -200, -300, SP), and the DC-10. They are characterized by a design that primarily addressed strength and fail-safe criteria while little or no attention was paid to incorporating corrosion protection into the design.

The second generation of jet transport airplanes, which were designed in the 1970s and the 1980s, include the B-737 (-300, -400, -500); B-747 (-400); B-757; B-767; MD-81, -82 and –83; MD-88; MD-11; and F-100. In addition to the strength and fail safety requirements, these airplanes are characterized by the incorporation of durability and damage tolerance standards into the design. It was realized that corrosion in aircraft was becoming an economic burden and could possibly become detrimental to the structural integrity of the airplane. Thus, as part of the durability standards, airframe manufacturers started to use corrosion-inhibiting primers and sealants for the faying surfaces of lap joints and fastener holes. Moreover, the Federal Aviation Administration (FAA) issued Airworthiness Directives (AD) related to corrosion control in design and maintenance.

The third generation of jet transport airplanes include the B-777 and the new generation B-737 (-600, -700, and -800) and B-747 (-400). In addition to the key characteristics of the first- and second-generation airplanes, these airplanes are characterized by the incorporation of significant improvements in corrosion prevention and corrosion control in design.

Corrosion Definition

The corrosion control program in the AD defines three levels of corrosion. It should be noted that the various modes of corrosion are not included in these definitions. Only the total loss of material, which affects the load-carrying capacity of a structure, is defined.

Level One Corrosion

- Corrosion damage occurring between successive inspections that is local and can be reworked or blended out within the allowable limits, as defined by the manufacturer.
- Corrosion damage that is local and exceeds allowable limits, but can be attributed to an event not typical of the operator's usage of other airplanes in the same fleet (e.g., mercury or acid spill).
- Operator experience over several years has demonstrated only light corrosion between successive inspections, and latest inspection and cumulative blend-out now exceed allowable limit.

Level Two Corrosion

- Corrosion occurring between successive inspections that requires rework or blend-out of structural elements as defined by the original equipment manufacturer's structural repair manual.

Level Three Corrosion

- Corrosion found during the first or subsequent inspections that is determined (normally by the operator) to be a potentially urgent airworthiness concern that requires expeditious action.
- In addition to the degree of corrosion, the extent of corrosion is taken into consideration. The appearance of corrosion on a single skin panel, single stringer, or single frame, where it does not affect any adjacent members, is defined as local corrosion. Widespread corrosion is defined as corrosion on two or more adjacent frames, chords, stringers, or stiffeners.
- The baseline program is designed to eliminate severe corrosion on airplanes and to control corrosion of all primary structures to Level One or better, meaning minor corrosion that never affects the airworthiness of the aircraft. Level Two and Level Three Corrosion must be reported to the airplane manufacturer, who uses the reported data to determine any actions required to ensure continuing airworthiness and economic operation.

Maintenance Schedule

A typical maintenance program begins with nightly inspections of each airplane, which consists of a detailed visual inspection and a review of the pilot's report. There are then scheduled periodic inspections:

<u>A Check</u> – This is a more detailed visual inspection conducted every 4 to 5 days after 65 to 75 flying hours. The interior and the exterior of each airplane is visually checked for general

condition and any obvious damage, with particular attention given to areas where exposure to accidental or environmental damage may have occurred.

B Check – This check occurs approximately every 30 days. Specific access panels are removed for inspection. In addition to engine servicing, other safety and airworthiness items are checked as well.

C Check – This is performed every 12 to 18 months after the aircraft has flown about 5,500 hours. It is an in-depth, extended, heavy structural and maintenance check.

D Check – This is the most comprehensive inspection, conducted after 20,000 to 25,000 flying hours. The paint is removed from the exterior, and the interior of the airplane is completely stripped to allow for close inspection of all structural members of the fuselage.

AREAS OF MAJOR CORROSION IMPACT

The corrosion cost in the aircraft sector can be broken down into three major elements.

- Cost of engineering and materials that are incorporated into a new aircraft. Only in the past 10 years have airframe manufacturers paid serious attention to the corrosion-conscious design and manufacturing of aircraft. Corrosion awareness has been evidenced by selection of more corrosion-resistant materials, specific design features, and the application of corrosion-inhibiting compounds and sealants.

- Cost of maintenance and unscheduled downtime. A significant percentage of the corrosion cost in this sector can be attributed to maintenance of the older airframes, which have little or no corrosion protection incorporated into their structures.

- Loss in asset value (depreciation). Depending on the level of attention paid to corrosion during the various maintenance activities, resale or lease values may vary considerably.

Design and Engineering

Few cost data are available on corrosion-specific engineering and manufacturing of aircraft. However, for one of the latest models, the B-777, some cost information is available(9), that can be extrapolated to the fleet.

The cost of incorporating corrosion control in the structural design of the B-777 was estimated at 100,000 engineering-hours for a total cost of approximately $20 million. The required testing and material to support this design adds another $5 million. Therefore, the total cost to design a corrosion-tolerant airplane of the size of the B-777 can be estimated at $25 million. In order to implement the corrosion design features, approximately 113 kg of corrosion-inhibiting compounds are needed. At a current cost of $238/kg, the total cost per airplane is approximately $30,000. Furthermore, about 200 hours of technician labor are required to apply these compounds for an estimated labor cost of $15,000. Therefore, the total cost per airplane to install corrosion-inhibiting compounds is $45,000.

Extrapolation of the numbers obtained for one particular airplane to the entire fleet is based on the following statistics:

1. In 1998, U.S. manufacturers delivered eight different jet aircraft: B-737, B-747, B-757, B-767, B-777, MD-11, MD-83, and MD-90.

2. The total number of jet aircraft built in the United States in 1998 is 544.
3. It is assumed that each type of aircraft delivered in 1998 has similar corrosion design features and design costs ($25 million).
4. The cost to implement the corrosion design is the same for each of the aircraft types ($45,000 per aircraft).

Based on these statistics, the total design cost for the eight types of U.S.-built jet aircraft delivered in 1998 is estimated at $200 million and the corrosion fraction of the total manufacturing cost for 544 airplanes delivered in 1998 is estimated at $25 million (544 x $45,000). This gives a total design and engineering cost of $225 million.

Maintenance and Unscheduled Downtime

Maintenance Costs

Maintenance cost is part of the total operating cost. The total operating cost also includes flying operations, passenger services, aircraft and traffic servicing, promotion and sales, depreciation, and amortization. Table 3 shows the total annual operating and maintenance expenses for domestic and international U.S. carriers.(10)

Table 3. Operation and maintenance expenses of U.S. air carriers for calendar years 1977–1997.(10)

	DOMESTIC			**INTERNATIONAL**		
Year	**Operating Expenses ($ x million)**	**Maintenance Expenses ($ x million)**	**Maintenance Expenses (% of Total)**	**Operating Expenses ($ x million)**	**Maintenance Expenses ($ x million)**	**Maintenance Expenses (% of Total)**
1977	$15,166	$2,001	13.2%	$3,852	$450	11.7%
1978	$17,172	$2,155	12.5%	$4,355	$498	11.4%
1979	$21,522	$2,457	11.4%	$5,505	$571	10.4%
1980	$26,409	$2,758	10.4%	$6,766	$616	9.1%
1981	$29,051	$2,822	9.7%	$6,574	$540	8.2%
1982	$29,476	$2,709	9.2%	$6,452	$512	7.9%
1983	$31,186	$2,878	9.2%	$6,693	$548	8.2%
1984	$33,812	$3,176	9.4%	$7,485	$677	9.9%
1985	$36,311	$3,604	9.9%	$7,984	$768	9.6%
1986	$39,959	$4,475	11.2%	$8,458	$901	10.7%
1987	$43,925	$4,951	11.3%	$10,226	$1,096	10.7%
1988	$47,739	$5,643	11.8%	$12,403	$1,332	10.7%
1989	$52,460	$6,184	11.8%	$14,954	$1,724	11.5%
1990	$58,983	$6,921	11.7%	$18,915	$2,051	10.8%
1991	$56,939	$6,703	11.8%	$19,884	$2,094	10.5%
1992	$59,138	$6,906	11.7%	$21,716	$2,107	9.7%
1993	$60,921	$6,990	11.5%	$21,596	$1,916	10.4%
1994	$63,558	$7,274	11.4%	$21,693	$2,036	9.4%
1995	$66,224	$7,670	11.6%	$22,216	$2,253	10.1%
1996	$71,460	$8,276	11.6%	$24,147	$2,615	10.8%
1997	$75,615	$9,443	12.5%	$25,154	$2,878	11.4%

Source: GKMG Consulting Services, Inc., based on carrier Form 41 filings with U.S. DOT.

Note: Details may not add up to totals because of rounding, including scheduled and non-scheduled services for all certificated route air carriers and excluding supplemental air carriers, commuters, and air taxis.

The operating costs listed in the table are averages of specific aircraft with varying ages, with the older airplanes requiring higher maintenance than the newer airplanes. It is clearly indicated in the table that over the past 20 years, the percentage average cost of maintenance has not changed significantly, varying between 8 and 13 percent of the total operating cost. For example, in 1997, the total operating costs were approximately $76 billion for domestic operations and $25 billion for international operations. The maintenance expenses, which include corrosion maintenance expenses, were about $9.5 billion for domestic operations and $3 billion for international operations (12.5 percent and 11.4 percent, respectively, of the total operating expenses).

According to the Air Transport Association (ATA) Annual Report of 1998, the operating costs of individual airplanes varied greatly.(11) Table 4 shows the average operating cost per hour for the most common U.S.-operated aircraft in 1997. The table indicates a wide range of operating costs – from $1,409 for a DC-9-10 to $6,447 for a B-747-100. Assuming that the average maintenance cost for that year is 12 percent (refer to table 3), an average maintenance cost can be calculated.

Table 4. Aircraft operating costs – 1997.(11)
(Figures are averages for most commonly used models.)

TYPE OF AIRCRAFT	**AIRCRAFT OPERATING COST PER HOUR**	**MAINTENANCE COST PER HOUR @ 12% OF OPERATING COST**
B-747-100	$6,447	$773.64
B-747-400	$6,859	$823.08
B-747-200/-300	$7,300	$876.00
B-747-F	$7,497	$899.64
L-1011-100/-200	$3,720	$446.40
B-777	$4,241	$508.92
DC-10-10	$5,281	$633.72
DC-10-40	$4,746	$569.52
DC-10-30	$6,078	$729.36
MD-11	$6,406	$768.72
A-300-600	$5,237	$628.44
L-1011-500	$3,829	$459.48
B-767-300ER	$3,558	$426.96
B-757-200	$2,675	$321.00
B-767-200ER	$3,348	$401.76
MD-90	$1,636	$196.32
B-727-200	$2,504	$300.48
B-727-F	$4,993	$599.16
A-320-100/-200	$2,177	$261.24
B-737-400	$2,124	$254.88
MD-30	$2,087	$250.44
B-737-300	$1,918	$230.16
DC-9-50	$1,923	$230.76
B-737-100/-200	$1,904	$228.48
B-737-500	$1,743	$209.16
DC-9-40	$1,500	$180.00
DC-9-30	$1,988	$238.56
F-100	$2,002	$240.24
DC9-10	$1,409	$169.08

Source: Air Transport Association (ATA) Annual Report, 1998.

Table 5 shows the maintenance costs for individual aircraft operated by U.S. carriers.(12) The data shown in this table indicate significant deviations from the numbers shown in table 4, which are based on 12 percent of the average operating cost of individual airplanes. The difference is particularly obvious for the older aircraft. For example, the total maintenance cost for the B-747-200 is shown in table 5 as $2,384 per block hour, while the same cost is shown in table 4 as $876. Similarly, for a B-727-200, table 5 shows a maintenance cost of $832 versus a cost of $321 in table 4. For the newer airplanes, the costs stated in the two tables are much closer. For example, the hourly maintenance costs for the B-747-400 is $1,206 and $823 in tables 5 and 4, respectively. The increase in maintenance cost discrepancy with the age of the airplane could be attributed to anincrease in corrosion and fatigue inspection and maintenance as the airplane ages.

Moreover, table 5 indicates significant differences in maintenance costs for specific aircraft operated by different airlines. For example, the hourly cost to maintain a B-747-200 is $2,675 by Northwest Airlines and $1,541 by United Airlines. This difference in maintenance cost data is primarily the result of a difference in airframe maintenance costs. In addition, it may be noted that the depreciation of the United B-747-200 is more than twice that of the Northwest B-747-200. The maintenance costs suggest a difference in maintenance practices between the two operators. Assuming that the aircraft are of approximately the same age, a higher maintenance cost and also a lower rate of depreciation would indicate Northwest Airlines' intent to own or lease these aircraft for a longer time than United Airlines.

Table 5. 1998 Maintenance cost (per block hour) for individual aircraft.(12)
(AK-Alaska; AA-American; CO-Continental; DL-Delta; NW-Northwest; TW-TWA; UA-United Airlines;
HP-America West; WN-Southwest; US-US Airways)

B-727-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		78	22	129	40	23	75				367	
Airframe Maint ($)		373	482	190	243	686	473					340
Engine Maint ($)		219	110	151	230	44	220					177
Maint Burden ($)		484	314	203	56	364	458					315
Total Maint ($)		1,076	906	544	529	1,094	1,151					832
Block Hours/Day		8.1	9.8	8.8	7.6	8.2	8.3					8.4
Maint / Day ($)		8,716	8,879	4,787	4,020	8,971	9,553					6,989
B-737-100/-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			3	54			25	18	37	64	201	
Airframe Maint ($)			240	114			222	206	921	259		343
Engine Maint ($)			12	106			146	207	33	84		96
Maint Burden ($)			134	131			422	182	42	356		216
Total Maint ($)			386	351			790	595	996	699		636
Block Hours/Day			9.1	10.1			7.8	9.7	10.5	9.3		9.6
Maint / Day ($)			3,513	3,545			6,162	5,772	10,458	6,501		6,288
B-737-300	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			92	21			101	46	207	85	552	
Airframe Maint ($)			159	113			146	245	123	151		147
Engine Maint ($)			6	238			179	241	132	181		140
Maint Burden ($)			88	209			381	110	42	246		150
Total Maint ($)			253	560			706	596	297	578		437
Block Hours/Day			10.2	9.4			10.3	11.3	11.2	10		10.6
Maint / Day ($)			2,581	5,264			7,272	6,735	3,326	5,780		4,632

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).[(12)]

B737-400	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number	37									54	91	
Airframe Maint ($)	69									68		68
Engine Maint ($)	4									209		112
Maint Burden ($)	26									22		24
Total Maint ($)	99									299		204
Block Hours/Day	11.6									9.6		10.4
Maint / Day ($)	1,148									2,870		2,122
B737-500	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			67				57		24		148	
Airframe Maint ($)			94				327		137			188
Engine Maint ($)			207				179		12			161
Maint Burden ($)			159				401		42			228
Total Maint ($)			460				907		191			577
Block Hours/Day			10.1				9.8		11.1			10.1
Maint / Day ($)			4,646				8,889		2,120			5,828
B747-100	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number							5				5	
Airframe Maint ($)							421					421
Engine Maint ($)							352					352
Maint Burden ($)							845					845
Total Maint ($)							1,618					1,618
Block Hours/Day							10.2					10.2
Maint / Day ($)							16,504					1,6504
B747-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number					25		9				34	
Airframe Maint ($)					724		394					639
Engine Maint ($)					968		343					808
Maint Burden($)					983		804					937
Total Maint ($)					2,675		1,541					2,384
Block Hours/Day					9.6		9.2					9.5
Maint / Day ($)					25,680		14,177					22,648
B747-400	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number					10		34				44	
Airframe Maint ($)					361		396					388
Engine Maint ($)					549		143					235
Maint Burden ($)					508		604					583
Total Maint ($)					1,418		1,143					1206
Block Hours/Day					12.6		12.6					12.6
Maint / Day ($)					17,867		14,402					15,196
B757-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		95	32	97	48		96	13		34	415	
Airframe Maint ($)		119	143	98	256		229	172		195		165
Engine Maint ($)		276	5	192	212		95	184		251		182
Maint Burden ($)		115	79	174	152		418	137		137		203
Total Maint ($)		510	227	464	620		742	493		583		550
Block Hours/Day		10.7	10.4	11.5	11.6		11	13		10.7		11.1
Maint / Day ($)		5,457	2,361	5,336	7,192		8,162	6,409		6,238		6,105

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).(12)

B-767-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		30		15		11	19			12	87	
Airframe Maint ($)		418		130		491	372			212		338
Engine Maint ($)		178		381		84	224			115		196
Maint Burden ($)		449		304		708	596			112		437
Total Maint($)		1,045		815		1,283	1,192			439		971
Block Hours/Day		10.3		10.4		12.6	10.9			13.9		11.3
Maint / Day ($)		10,764		8,476		16,166	12,993			6,102		10,972

B-767-300	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		45		68		4	27				144	
Airframe Maint ($)		151		140		142	120					140
Engine Maint ($)		183		193		103	197					188
Maint Burden ($)		147		223		246	368					225
Total Maint ($)		481		556		491	685					553
Block Hours/Day		13.7		13		13.5	12.8					13.2
Maint / Day ($)		6,590		7,228		6,629	8,768					7,300

B-777	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number							34				34	
Airframe Maint ($)							391					391
Engine Maint ($)							–					–
Maint Burden ($)							403					403
Total Maint ($)							718					718
Block Hours/Day							13.6					13.6
Maint / Day ($)							9,765					9,765

Fokker-100	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		75								40	115	
Airframe Maint ($)		199								123		173
Engine Maint ($)		81								173		112
Maint Burden ($)		145								417		236
Total Maint ($)		425								713		521
Block Hours/Day		8.7								8.2		8.5
Maint / Day ($)		3,698								5,847		4,429

L-1011-1-250	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number				23							23	
Airframe Maint ($)				318								318
Engine Maint ($)				267								267
Maint Burden ($)				349								349
Total Maint ($)				934								934
Block Hours/Day				9.8								9.8
Maint / Day ($)				9,153								9,153

L-1011-1-500	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number				14							14	
Airframe Maint ($)				315								315
Engine Maint ($)				264								264
Maint Burden ($)				367								367
Total Maint ($)				946								946
Block Hours/Day				9.1								9.1
Maint / Day ($)				8,609								8,609

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).(12)

MD-11	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		11		15							26	
Airframe Maint ($)		619		230								375
Engine Maint ($)		313		131								199
Maint Burden ($)		505		255								348
Total Maint ($)		1,437		616								922
Block Hours/Day		11.2		13.9								12.7
Maint / Day ($)		16,094		8,562								11,709
DC-9-30	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			21		116	34				48	219	
Airframe Maint ($)			272		324	288				188		282
Engine Maint ($)			46		192	168				229		182
Maint Burden ($)			169		233	389				382		286
Total Maint ($)			487		749	845				799		750
Block Hours/Day			8.6		7.7	8.4				8.3		8.0
Maint / Day ($)			4,188		5,767	7,098				6,632		6,000
DC-10-30	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		5	30		16		8				59	
Airframe Maint ($)		461	533		327		1039					526
Engine Maint ($)		514	426		535		576					482
Maint Burden ($)		501	507		133		726					423
Total Maint ($)		1,476	1,466		995		2,341					1,431
Block Hours/Day		9.4	11.4		11.5		9.4					11.0
Maint / Day ($)		13,874	16,712		11,443		22,005					15,741
MD-80	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number	39	260	69	120	8	72				31	599	
Airframe Maint ($)	236	169	328	109	403	151				68		175
Engine Maint ($)	96	90	73	99	–	113				–		84
Maint Burden ($)	134	186	213	124	626	239				431		196
Total Maint ($)	466	445	614	332	1,029	503				420		455
Block Hours/Day	11.3	10	9.4	9.9	8.2	10.3				9		10.1
Maint / Day ($)	5,266	4,539	5,772	3,287	8,438	5,181				3,780		4,596

Maintenance Trends

An analysis of 25 years of the DOT Form 41 commercial fleet maintenance cost data indicated that for all aircraft types, the maintenance cost for engines remained relatively constant.(13) However, trend diagrams, such as those shown in figure 5, clearly indicate that airframe maintenance costs started to increase in the mid-1980s, which coincided with the fleet leader reaching its design life of 20 years. The maintenance trend diagram in figure 5 represents the maintenance costs of 60 Boeing Classic 747-100/-200 airplanes for a period of 25 years. According to the diagram, the average fleetwide Boeing Classic 747 airframe maintenance grew at an annual rate of 7 percent from 1985 to 1998. A summary diagram in figure 6 shows that the increase in maintenance cost growth rates over the life of an airframe ranges from 3.5 percent for the DC-9 to 9 percent for the DC-10. Figure 6 also shows the average age of five different aircraft as a function of cost per flight-hour. The arrows in the figure indicate that the oldest aircraft or fleet leaders are the B-747 and the B-727. The figure shows the high airframe cost of the B747 and DC10 components compared with those of the smaller DC-9, B-737, and B-727 airframes.

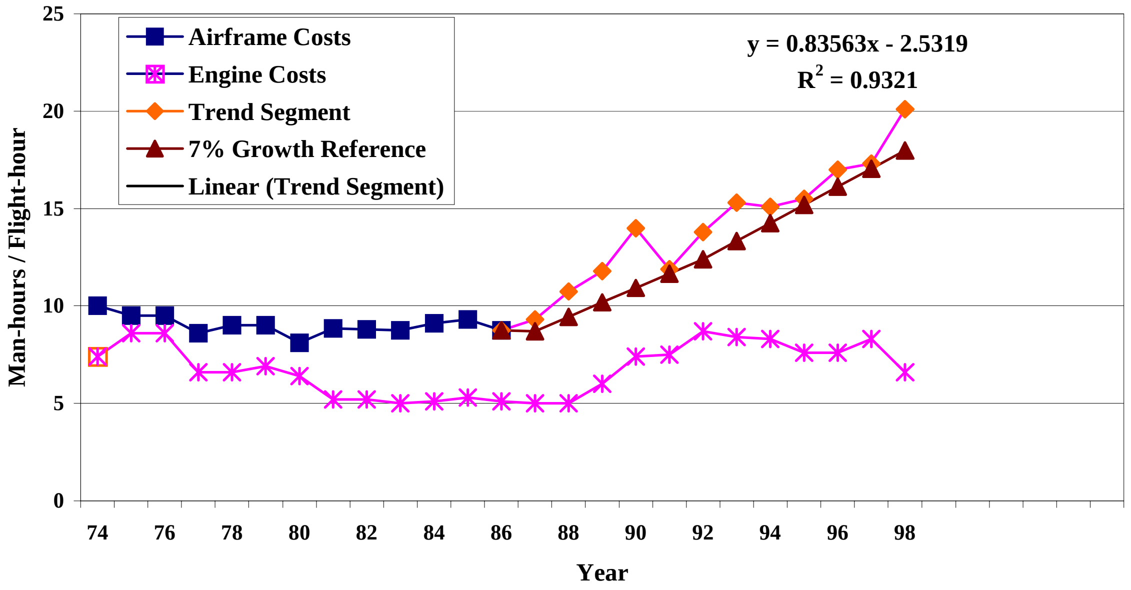

Figure 5. Maintenance trend analysis – B-747-100/-200.(13)

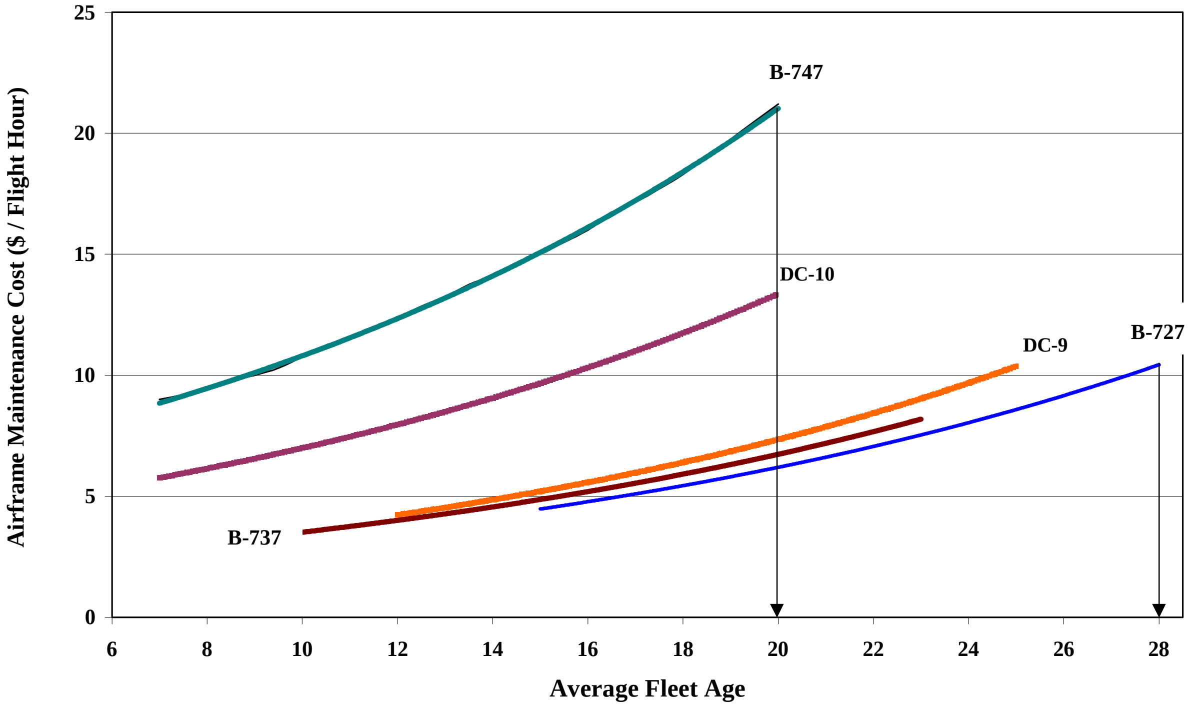

Figure 6. Maintenance trend analysis showing airframe maintenance cost per flight-hour as a function of average fleet age.(13)

Airplane Maturation

The level of maintenance depends on the age of an airplane. The service life of an airplane can be divided into three different phases: the newness phase, the mature phase, and the aging or post-design life phase. The airplane mature phase is defined as beginning at the end of the first major comprehensive maintenance cycle (D-check) and lasting through the second maintenance cycle.(14) The mature phase starts at about the fifth or sixth year of operation and ends arbitrarily at 25,000 flight-hours. For an aircraft utilized about 2,500 hours per year, the newness phase lasts for the first 5 to 6 years, and the mature phase occurs the following 5 to 6 years. Beyond this point, industry maintenance cost data indicate that an airframe enters its aging phase. Boeing has developed an analytical/empirical model to predict the maintenance costs of different types of aircraft. Figure 7 shows the results of the model in the form of maturation diagrams. The figure shows the airframe maturity factor as a function of the age of specific aircraft. This factor is an age-related multiplying factor for a total aircraft maintenance cost (see table 6). Assuming that most of the maintenance costs are incurred during depot maintenance, maturity diagrams for light (A- and B-checks) and heavy maintenance (C- and D-checks) were developed. These are indicated in figure 7 as airframe and heavy maintenance maturity factor diagrams.

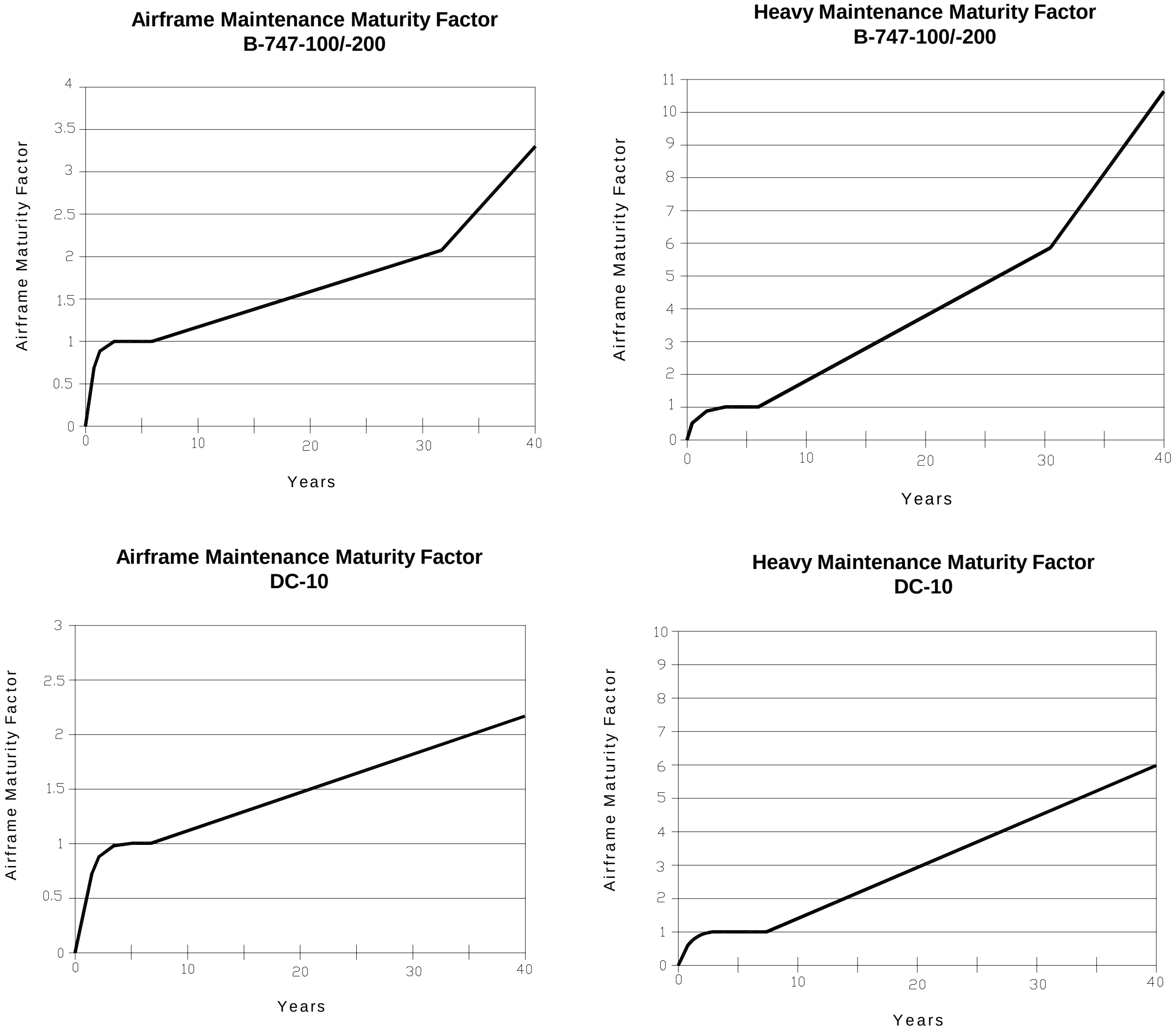

Figure 7. Airframe maintenance and heavy maintenance maturity diagrams.(14)

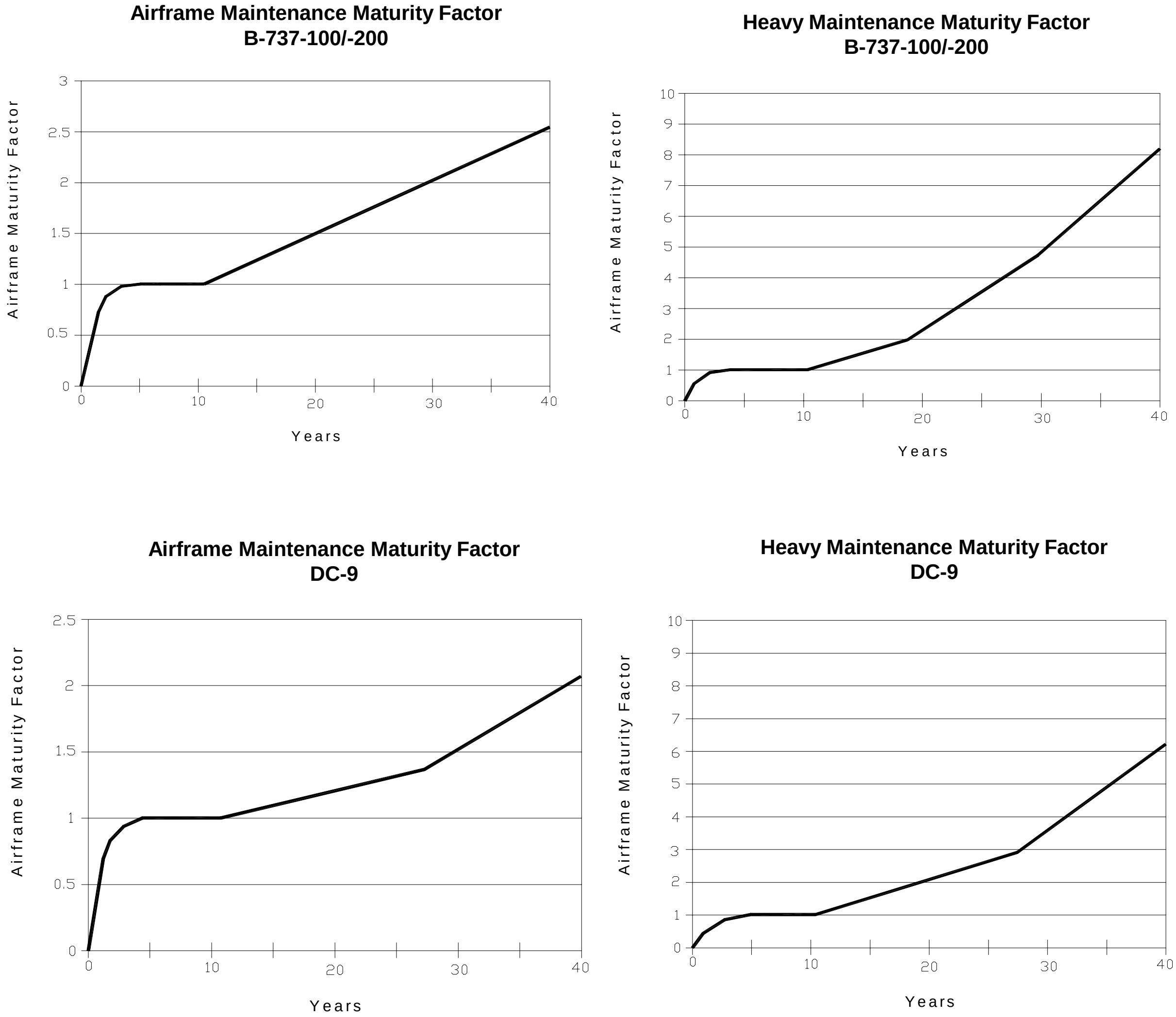

Figure 7. Airframe maintenance and heavy maintenance maturity diagrams (continued).(14)

The estimated mature maintenance costs in 1999 in dollars per flight-hour (maturity factor = 1) are shown in table 6.(15) The total maintenance costs shown in the table are based on labor and material for the airframe and the engine, as well as shipping and handling. Based on the curves and the estimated maturation maintenance cost, the average annual maintenance cost of an airplane can be calculated. For example, if at year 35 the airframe maturity factor is 2 and the heavy maintenance maturity factor is 6, one would multiply the mature values in current dollars by those factors to predict the average annual costs when the airplane is 23 years old. It should be noted that in the aging phase, the rate of increase of both the airframe maturity factor and the heavy maintenance maturity factor varies significantly for the different airplanes, but that the escalation of maintenance cost is dominated by the medium (C-check) and heavy (D-check) maintenance cost increases.

The diagram in figure 5 and the data indicating a maturity factor of 1 in table 6 refer to the total maintenance cost, which includes corrosion- and fatigue-related maintenance. These two modes of deterioration are intertwined and, therefore, are important factors to be considered as the Corrosion Prevention and Control Programs (CPCPs) and aging programs are implemented. Metal is appropriately removed when corrosion is detected; as a result of this removal, the airframe becomes less fatigue-resistant and this leads to an increased number of non-routine repairs during the heavy checks. The cost numbers in table 6 are estimates and do not include the maintenance burden. The reported cost numbers in table 5 include the maintenance burden, which results in a higher total maintenance cost.

Table 6. Estimated mature maintenance cost in 1999 (U.S. dollars per flight-hour).(15)

AIRPLANE	737-200	737-300	737-700	747-200	747-400	DC10-30	DC8-55F	DC9-30
LABOR								
Airframe	62.67	65.59	52.68	186.89	180.34	154.42	181.82	59.53
Engine	15.68	13.80	11.22	72.91	56.49	53.78	39.48	16.74
LABOR (Subtotal)	**78.35**	**79.39**	**63.90**	**259.80**	**236.83**	**208.20**	**221.30**	**76.27**
MATERIAL								
Airframe	46.58	46.63	42.24	201.13	234.57	159.96	145.04	46.49
Engine	55.26	109.09	100.04	511.83	511.48	432.07	92.20	57.19
Shipping/Handling	7.13	10.90	9.96	49.91	52.22	41.44	16.61	7.26
Contractor’s Surcharge	–	–	–	–	–	–	–	–
MATERIAL (Subtotal)	**108.96**	**166.63**	**152.23**	**762.86**	**798.28**	**633.47**	**253.84**	**110.95**
TOTAL DIRECT	**187.31**	**246.02**	**216.13**	**1,022.67**	**1,035.11**	**841.67**	**475.14**	**187.22**
OVERHEAD	**188.03**	**190.55**	**153.36**	**623.53**	**568.40**	**499.69**	**531.13**	**183.05**
TOTAL MAINTENANCE	**$375.34**	**$436.57**	**$369.49**	**$1,646.20**	**$1,603.51**	**$1,341.36**	**$1,006.27**	**$370.27**

Fleet Costs

In 1983, the International Air Transportation Association (IATA) conducted a survey of international carriers on the cost of aircraft corrosion.(16) The IATA document, *Guidance Material on Design and Maintenance Against Corrosion of Aircraft Structures*, dated November 1983, states that the cost of aircraft corrosion can be expressed in several ways:

- Direct corrosion cost per flight-hour is between $8 and $20, depending on the operator and aircraft type (not including maintenance overhead), based on 1982 costs.
- Corrosion fraction of direct airframe maintenance costs is between 6 and 8 percent.
- Total annual direct cost for IATA member airlines would be close to $200 million based on 1982 operations.

The above-reported values represent the costs for a range of airlines and aircraft types. The lower value is very conservative and is largely based on one operator’s actual modification cost alone. The higher value is more likely to be closer to the actual corrosion cost since it is based on a breakdown of actual modification, routine maintenance, and inspection costs. Furthermore, it was stated in the document that the major cost component associated with corrosion prevention and control is the cost of labor. An additional cost that is not reflected in the IATA numbers is the unscheduled downtime.

When assuming that in 1982 the cost of corrosion was 8 percent of the total maintenance cost [$3,221 million for domestic and international carriers (see table 3(11))], the total cost of corrosion in 1982 dollars can be estimated at $257 million. This cost is close to the IATA estimate of $200 million.

In table 7, the total 1996 maintenance expenses are presented for the various major national, regional, and cargo airlines.(10) Presently, the cost of corrosion maintenance is estimated at between 8 percent of the total maintenance expenses for new airplanes and 20 percent of that of old airplanes.(9) Assuming that the average corrosion maintenance expense is 15 percent of the total maintenance expense, the corrosion maintenance expense for the different carrier groups was calculated. The total maintenance expense of $11.5 billion in table 7 is in approximate agreement with the total maintenance expense shown in table 3. Table 3 shows that the total maintenance expenses in 1996 and 1997 are $10,891 billion and $12,321 billion, respectively.

Summing up the estimated 1996 corrosion maintenance costs results in a total expense of approximately $1.7 billion. This number includes labor, materials, and consumables, but does not include the cost of unscheduled downtime.

Table 7. U.S. carriers' maintenance expenses (1996 dollars).(10)

CARRIER	MAINTENANCE EXPENSE ($ x million)	% OF TOTAL OPERATING EXPENSES	CORROSION MAINTENANCE COST @ 15% OF MAINTENANCE EXPENSE ($ x million)
AK	116.9	8.83	17.5
America West	199.4	11.56	29.9
AA	1,873.5	13.00	281.0
CO	665.0	11.63	99.7
DL	1,114.8	8.86	167.2
NW	1,125.2	12.81	168.8
WN	353.9	10.75	53.1
TW	455.1	13.55	68.3
UA	2096.9	13.02	314.5
US	935.6	11.82	140.3
TOTAL MAJOR	**$8,936.2**	**11.58%**	**$1,340.4**
AirTran Airlines	82.5	28.37	12.4
Aloha	40.2	17.67	6.0
American TransAir	99.1	13.46	14.9
Frontier	33.3	19.85	4.7
Hawaiian	95.9	23.84	14.4
Midway	22.2	13.00	3.3
Midwest Express	32.8	12.06	4.9
Reno	48.3	11.38	6.8
World	66.0	22.55	9.9
TOTAL NATIONAL	**$515.4**	**18.02%**	**$77.3**
Air Wisconsin	27.0	19.69	4.1
Atlantic Southeast	68.6	22.46	10.3
Continental Express	78.4	20.08	11.8
Executive	23.1	20.28	3.5
Horizon	62.8	21.05	9.4
Simmons	78.1	17.03	11.7
Trans States	29.7	16.24	4.5
TOTAL REGIONAL	**$367.8**	**19.55%**	**$55.2**

Table 7. U.S. carriers' maintenance expenses (1996 dollars) (continued).(10)

CARRIER	MAINTENANCE EXPENSE ($ x million)	% OF TOTAL OPERATING EXPENSES	CORROSION MAINTENANCE COST @ 15% OF MAINTENANCE EXPENSE ($ x million)
Arrow Air	33.7	36.09	5.5
Atlas	26.1	7.57	3.9
DHL	105.3	9.17	158.0
Emery	62.3	28.03	9.4
Evergreen	43.5	19.45	6.5
Federal Express	850.9	7.19	127.6
Polar Air Cargo	87.3	25.89	13.1
Southern Air Transport	85.6	46.63	12.8
UPS	410.0	22.69	61.5
TOTAL CARGO	**$1,707.7**	**22.52%**	**$256.1**
GRAND TOTAL	**$11,527.1**		**$1,729.1**

Source: GKMG Consulting Services, Inc.

Unscheduled Downtime

A typical cost for U.S. domestic operations is $2,500 per delay/interruption-hour.(9) When an annual downtime for an older airplane, such as a B-727, of 40 hours is assumed, an additional cost of $100,000 can be estimated. Assuming that airplanes at or beyond their design service life of 20 years (a total of 1,034 according to table 1) have an average annual downtime of 40 hours and assuming that 50 percent results from corrosion, the total annual downtime cost due to corrosion is approximately $50 million (1,034 planes x 40 hours per plane x $2,500 per hour x 0.5).

Older airplanes will also be subject to increased scheduled and unscheduled maintenance downtime to incorporate modifications, to comply with aging aircraft programs, and to complete increased maintenance required as the airplane ages. For example, comparing the B-727 with the B-737-500, the revenue loss for a B-727 due to scheduled and unscheduled maintenance can range from 15 to 25 flight-days. Using the same definition for older airplanes and assuming that 50 percent of unscheduled maintenance (13 days) is due to corrosion, a total corrosion-related cost can be estimated at $250 million. Finally, a 2.5 percent reduction in passenger load factor is assumed on the B-727 to address the loss of passengers at full load due to performance degradation, and some reduction in revenue can be assumed due to passenger preference issues. The resulting cost could not be estimated.

Corrosion Maintenance Costs for Older Airplanes

The following empirical equations are used by Boeing to calculate the cost of corrosion maintenance for the older individual aircraft B-727-100/-200, B-737-100/-200, and B-747-100/-200:

Corrosion Maintenance Cost = Routine Maintenance + Non-Routine Repair + Parts and Consumables

For the B-727-100/-200 and the B-737-100/-200, the values are estimated as:

Routine Maintenance	4,500 h x $X per hour
Non-Routine Repair	3,000 h x $X per hour
Parts and Consumables	$4,500

where X = technician's cost (estimated at $65/hr)

For the B-747-100/-200, the values are estimated as:

Routine Maintenance	20,000 h x $X per hour
Non-Routine Repair	80,000 h x $X per hour
Parts and Consumables	$80,000.

where X = technician's cost (estimated at $65/hr).

The cost calculations are based on a 6-year period, which is the typical period between heavy maintenance (D-check).

The corrosion maintenance costs for the B-757 and B-767 are similar to that of the B-727-100/-200 and the B-737-100/-200.

The newer versions of the B-737 and the B-747, i.e. B-737-300/-400, B-737-600/-700/-800, and B-747-1400, have a 3 to 16 percent less total corrosion maintenance cost than the older versions of these airplanes. Finally, the B-777 has similar corrosion maintenance costs to the B-737-800. Table 8 summarizes the results of the corrosion maintenance costs calculated.

Table 8. Total cost of corrosion maintenance per year.

AIRPLANE TYPE	CORROSION COST
B-727-100/-200	$88,750
B-737-100/-200	$88,750
B-747/100/-200	$1,096,667
B-757	$88,750
B-767	$88,750
B-737-300/-400	$86,088
B-737-600/-700/-800	$74,976
B-747-400	$921,200
B-777	$74,976

According to one major airline, the average cost of corrosion maintenance is approximately $200,000 per airplane per year or 10 to 12 percent of the total maintenance cost.

Loss in Asset Value (Depreciation)

Depending on the level of attention paid to corrosion during the various maintenance activities, resale or lease values of aircraft may vary. The resale value of a pre-owned plane is directly affected by its (possibly corroded) appearance and any corrosion-related defects an inspector or appraiser may observe. In the current sector description, no estimate was made due to the large variety in planes and many other factors that play a role in the resale value of aircraft.

Total Cost of Corrosion

The total cost of corrosion for U.S. aircraft is estimated at $2.225 billion, including $0.225 billion for design and engineering, $1.7 billion for corrosion-related maintenance, and $0.3 billion for unscheduled downtime. No cost estimate was established for loss of asset value (depreciation).

CORROSION MANAGEMENT ASSESSMENT

Significant improvements have been made in the corrosion design of new airplanes. The airframe manufacturers have implemented many key design improvements over the past 25 years. Figure 8 shows some of these improvements for the B-747 since the early 1970s.(9) The improvements range from the replacement of corrosion-prone materials, such as aluminum alloy 7075-T6, to improved adhesive bonding processes, to the use of sealants in fastener holes and on faying surfaces, to the control of spillage, such as galley and lavatory fluids. Other airplane models have made similar improvements.

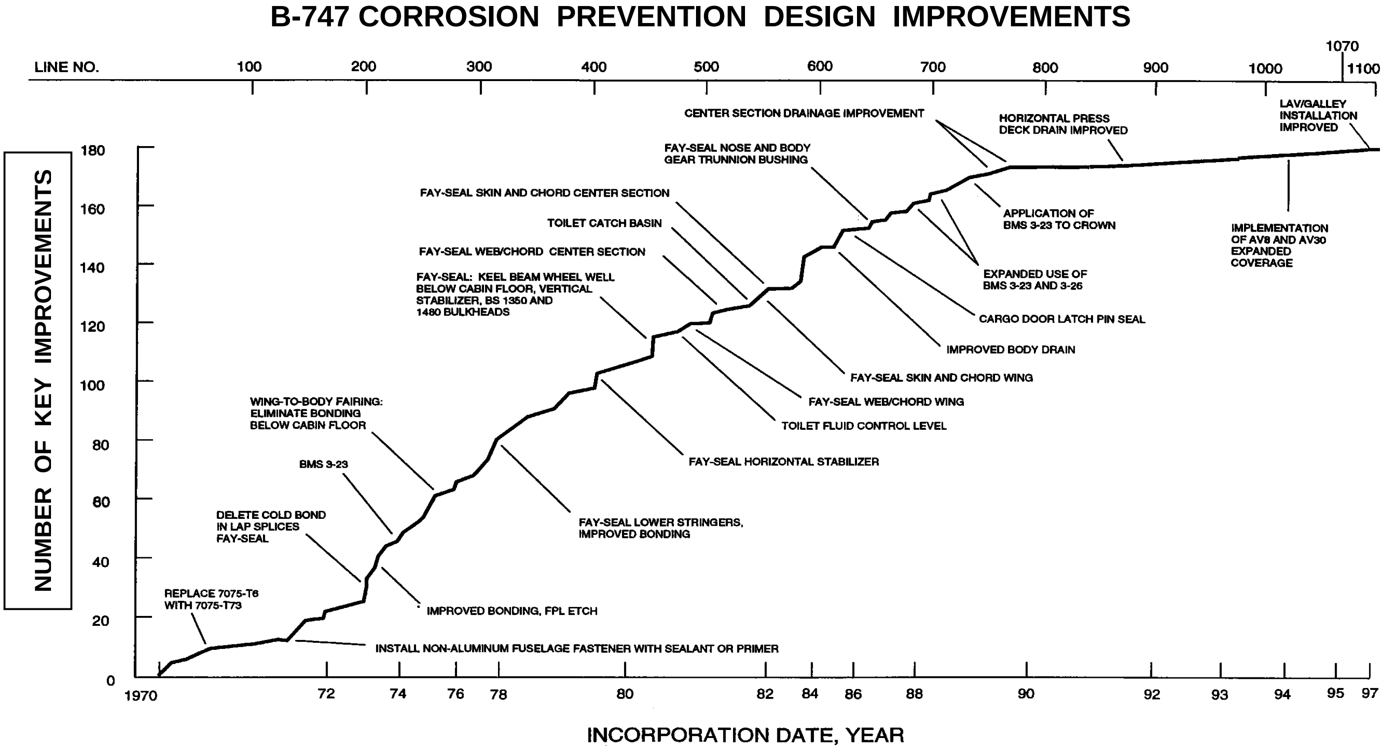

Figure 8. B-747 corrosion prevention design improvements.(9)

It must be understood that aggressive maintenance can mitigate and perhaps prevent corrosion in aging airplanes. In fact, a major U.S. domestic airline has stated that the degree to which an airline aggressively pursues corrosion prevention from the beginning of an airplane's maintenance life is the single most important measure affecting future maintenance costs.(17) In the same statement, it was pointed out that exposure to humid, coastal ground environments, as well as certain corrosive cargo materials, can play a very significant role, especially when accompanied by a less-than-aggressive approach to corrosion prevention and control. Some airlines with available resources, who are planning to keep their aircraft for many years, must be aggressive in their approach to preventing corrosion, especially when the airframe is exposed to harsh environments. However, if resources are unavailable, or the airplanes are expected to be sold, maintenance practices will seldom go beyond the minimum regulatory requirements. These issues will affect the maintenance cost escalation when the airplane has reached its aging phase, but also will affect the starting point at which the airplane will enter its aging phase.

Moreover, it is important that airlines apply state-of-the-art corrosion control techniques, even to the older airplane. The definitions used to describe the levels of corrosion (Levels 1, 2, and 3) are inadequate to characterize corrosion on an aircraft. Recent research examining corrosion in the lap joint of both commercial and military aircraft has indicated that metal loss alone cannot be relied upon as a measure of the severity of corrosion. Certain types of corrosion that do not contribute to significant loss in mass, such as pitting and intergranular corrosion, can have a significant detrimental effect on fatigue life.

Maintenance practices vary depending on the type of airline. For example, one major U.S. airline tracks corrosion problems by tail number of the aircraft and trend data to determine threshold levels for maintenance actions for the fleet. Inspections are performed on letter checks (major inspections) under FAA requirements every 9 months to 1 year. Because flight profiles and utilization cycles are very close for all the aircraft and since local basing environments have little influence on corrosion and other maintenance factors, all aircraft in the fleet are considered equal. As a result of this, the airline is able to predict the maintenance requirements of all of their airplanes with high accuracy, while maintaining at least 88 percent efficiency in their maintenance operations. Other airlines manage the maintenance of the airplanes in a different manner. For example, most of them do not track or manage any specific unique corrosion problems. In fact, the majority of the airlines perform better inspections specific to each type of airplane.

Generally, the maintenance manuals that go with the individual B-747-100 airplanes are used to conduct corrosion maintenance, and these maintenance procedures have typically not been updated to present standards. Specifically, when galleys and lavatories are removed, they are often not reinstalled properly using state-of-the-art sealants and CICs. However, if the corrosion control techniques described in the maintenance manuals for new generation airplanes (i.e., B-747-400) would be applied to the older airplanes, better corrosion control management can be accomplished. Finally, training and education of maintenance engineers and technicians play an important role in the corrosion management of airplanes. Only if these engineers and technicians are fully aware of all the aspects of corrosion inspection and maintenance of airplanes and have an understanding of the impact of good corrosion management on maintenance cost and structural integrity can airplanes be economically and safely operated beyond their design lives.

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