LIFE CYCLE COST ANALYSIS OF
AGING AIRCRAFT AIRFRAME
MAINTENANCE

By

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CHAPTER I

INTRODUCTION

Background of the Problem

Predicting the point at which an aircraft will become uneconomical to support requires a thorough understanding of aging aircraft maintenance trends and forecast modification requirements. Aging aircraft maintenance requirements may combine with FAA mandated avionics or noise compliance requirements (Stage III or IV) to mark the end of an aircraft's Economic Service Life (ESL). Individual aircraft must be evaluated regarding factors such as historical cyclic utilization, environmental basing history and previous maintenance history to provide an accurate snapshot of today's economic assessment (Rice, 1998). Today's economic value must then be projected forward considering future annual fleet cyclic utilization and forecast corrosion growth rates for each specific environmental area of operation (Cooke, 1998). High acquisition costs of replacement equipment are forcing both the military and commercial sectors to focus on Total Ownership Costs (TOC). Cumulative ownership costs over the 20, 30 and even 40 year life span of an aircraft can totally eclipse the initial acquisition costs and are driving a renewed interest in Life Cycle Cost modeling (Dhillon, 1989).

There are many economic factors that contribute to determining when an aircraft should be replaced. Typically the primary cost driver is increasing maintenance requirements due to the age of the aircraft. Increasing maintenance requirements drive up maintenance costs and drive down aircraft availability (NRC, 1997).

Since 1988, when an Aloha airlines jet experienced a catastrophic structural failure, airline and industry working groups have developed aging aircraft programs to inspect and modify various portions of an airframe. The costs to comply with "aging program" Air worthiness Directive (AD) requirements may be less than $500,000 for a DC-10, but more than $5 million for a 747-200 (Sweers, 1997). To definitively model cost growth, an understanding of each airframe design's inherent resistance to fatigue and corrosion is necessary.

A detailed LCC analysis must not only include the initial acquisition costs, but must also include both the implicit and explicit, operational and disposal costs (Figure 1).

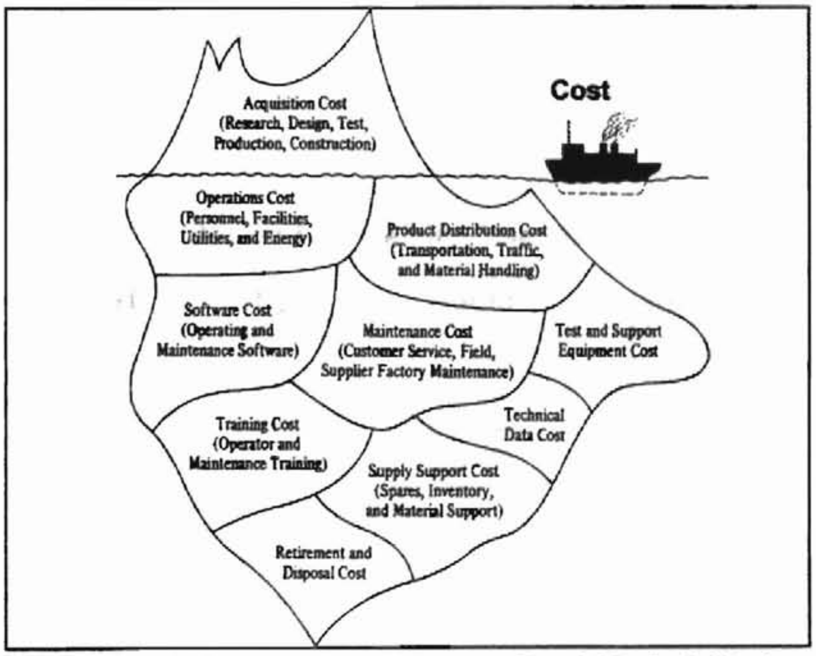
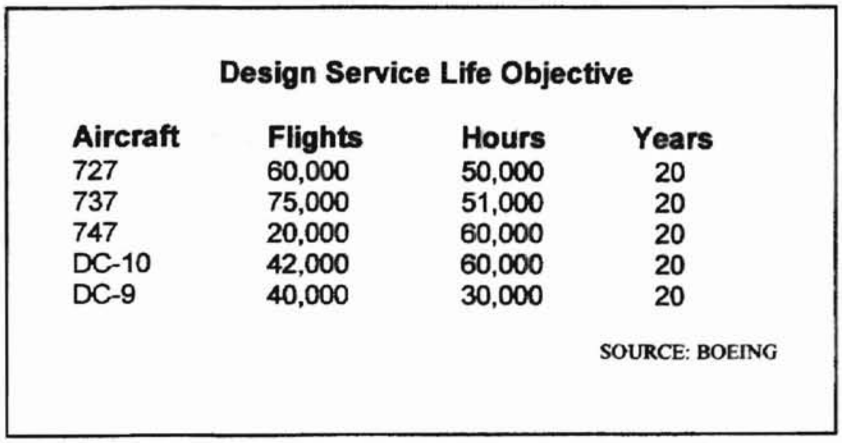


Figure 1. Life Cycle Cost Forecasts Should Include Both Implicit and Explicit Costs. Source: Blanchard.

Competing alternatives should recognize both the explicit monetary benefits such as: reduced fuel consumption and lower maintenance costs, plus attempt to quantify the implicit and rather subjective non-monetary benefits such as customer preference for a newer aircraft.

The FAA has recognized this trend to keep aircraft in service longer. In 1988 the U.S. large transport fleet totaled nearly 3,700 aircraft and had an average fleet age of 12.7 years. In just ten years, the heavy commercial transport fleet has grown to nearly 5,400 aircraft and the average age is now 15.8 years. It is estimated that ten years from now the average U.S. fleet age will be between 18 and 20 years old (Garvey, 1999).

This trend to keep aircraft longer must be reflected in the LCC forecasting methodology (Figure 2). Many of the heavy commercial transport aircraft were designed for between 20,000 and 60,00 flight cycles, and between 30,000 and 60,000 flight hours. The majority of the aircraft were also designed to meet a 20-year life expectancy.



Design Service Life Objective

Aircraft	Flights	Hours	Years
727	60,000	50,000	20
737	75,000	51,000	20
747	20,000	60,000	20
DC-10	42,000	60,000	20
DC-9	40,000	30,000	20

SOURCE: BOEING

Figure 2. Design Service Objectives for Boeing Built Aircraft.

The "bathtub" hazard rate (or failure rate) curve has been used to represent the failure behavior rate of many items (Figure 3). This curve is divided into major three parts: burn-in period (decreasing hazard rate region), useful life period (constant hazard rate region) and wear out period (increasing hazard rate region). Failures, which occur during the burn-in period, are normally due to design or manufacturing defects. The useful life period is characterized by unpredictable or random failures. This useful life portion remains constant until the onset of the wear-out or "Aging" period indicated by an increasing failure rate.

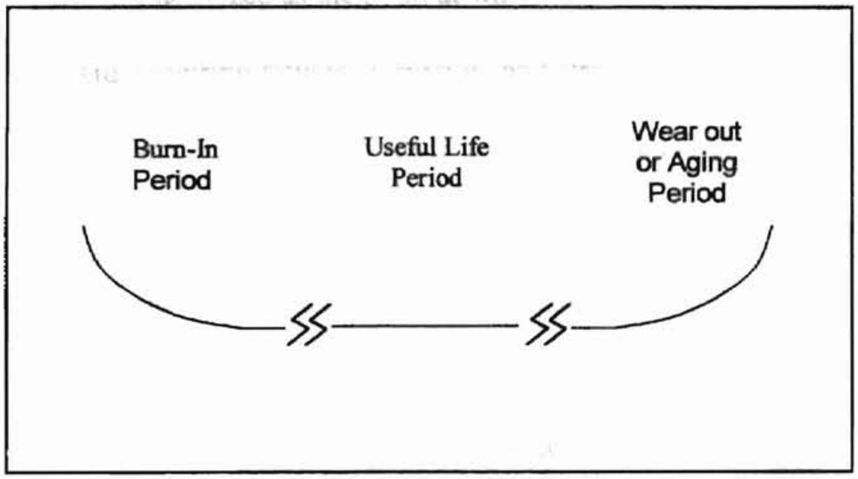


Figure 3. Failure Rate over the Life Expectancy of a System May Be Categorized into Three Distinct Failure Periods. Operation and Support Costs Closely Follow the System Reliability. Source: Blanchard.

Part failure rates are directly proportional to operational support costs. Many failures during the Burn-in or newness period however are covered by the manufacturers warranty and not the responsibility of the owner. Some of the reasons for this increasing failure rate during the aging phase may be due to inadequate maintenance, aging, corrosion, fatigue, incorrect overhaul practices and most likely a combination of all the above.

Statement of the Problem

Today no Life Cycle Cost model attempts to quantify the rate of airframe maintenance cost increases due to the effects of aging. MIL-HDBK-1530 defines aging aircraft as the point in time in which the aircraft: 1) has over flown it's design service goal, 2) is corroded, or 3) has reached the time of onset of widespread fatigue damage (WFD). It is further characterized as the point at which both the cost and operational burden associated with repairing fatigue, corrosion, and stress corrosion cracking (SCC) either by themselves or in combination, result in a significant departure from a newly manufactured aircraft. Today no industry recognized cost escalation factors exist which represent airframe maintenance cost increases due to aging.

The cost to maintain and operate aging aircraft is being reviewed to identify factors which must be included in the methodology to accurately assess the economic service life of aging aircraft. Recent GAO reports have been critical of increases in both depot maintenance man-hours (cost) and duration (downtime) of military aircraft. These GAO reports have associated these increases with the irreversible effects of aging. General Accounting Office. (1996). Report to Congressional Committees GAO/NSIAD-96-160.

This causal-comparative study will analyze a large population of commercial airframe maintenance data for trends, which may confirm maintenance growth as a function of age. Validating these perceived maintenance increases and quantifying the significance of this trend is necessary to accurately forecast future cost of ownership.

To accurately predict the Economic Service Life of an aircraft one must model total aircraft ownership costs of the subject aircraft (including aging considerations), and compare those costs to the costs of acquiring and operating an alternative aircraft. Aging fleet maintenance requirements must be also be combined with estimates to upgrade outdated avionics. These plans may include navigational upgrades required to comply with Future Air Navigation requirements, or Global Air Traffic Management requirements as well as safety modifications required by the Federal Aviation Administration.

Future mandatory navigation upgrades may include a Global Positioning System coupled to Flight Management System and Reduced Vertical Separation Minimum equipment. Safety upgrades may require the addition of an Enhanced Ground Proximity Warning System coupled to a second generation Traffic Alert and Collision Avoidance System. Also on the drawing board are new 300 channel Digital Flight Data Recorders, Cockpit Voice Recorders, and a more powerful Emergency Locator Transmitters. The need to comply with future FAA and ICAO mandated Stage III and future Stage IV noise requirements is also a political hot potato. Various civil airports (especially in Europe) are assessing the legality of excluding aircraft equipped with American made Hush Kits. Flight restrictions may limit the operating hours of hush-kitted aircraft or discouraging their operation through the use of higher landing fees. Each of these modifications, each with an individual subjective probability, needs to be quantified for possible inclusion in a total Cost of Ownership forecast.

Purpose of the Study

It is the purpose of this study to: 1) to confirm that aircraft airframe maintenance costs do indeed increase with the advancement of age, and 2) identify the magnitude of airframe maintenance growth anticipated with the onset of aging. The goal is to develop airframe growth factors that should be applied to cost analysis involving aging aircraft. This study will also provide a general methodology for accounting for key cost elements associated with heavy jet aircraft operations and support (O&S).

Research Hypothesis

It is hypothesized that a strong correlation exists between the age of an aircraft and its annual airframe maintenance costs. It is believed that aging airframe maintenance man-hours are significantly higher than those reported when the aircraft was less than twenty years old. The null hypothesis within this study therefore states that there is no statistically significant difference between airframe maintenance man-hours of aircraft prior to the on-set of aging (< 20 years old), versus airframe maintenance from the same general sample of aircraft when the aircraft are over 20 years of age. This study will convert reported Then-Year (TY) dollars, to Constant Year (CY) or base year 1998 (BY98) dollars to remove inflation. This study will focus on U.S. registered commercial aircraft with documented historical support costs.

Importance of the Study

Verifying and ultimately modeling the severity of airframe maintenance cost increases are typically the foundation of the larger Cost of Ownership (COO) study, which attempts to forecast total cost of ownership into the future. The COO study is then compared to alternative aircraft within an Economic Service Life (ESL) study in which cost projections from both aircraft are compared. Figure 4 depicts how the aging airframe maintenance trends will combine with the modification requirements within a COO. The COO study will introduce the additional major cost elements such as Personnel, Unit level consumption, Intermediate level maintenance, Contractor Support, Sustaining support, Indirect support and Disposal costs.

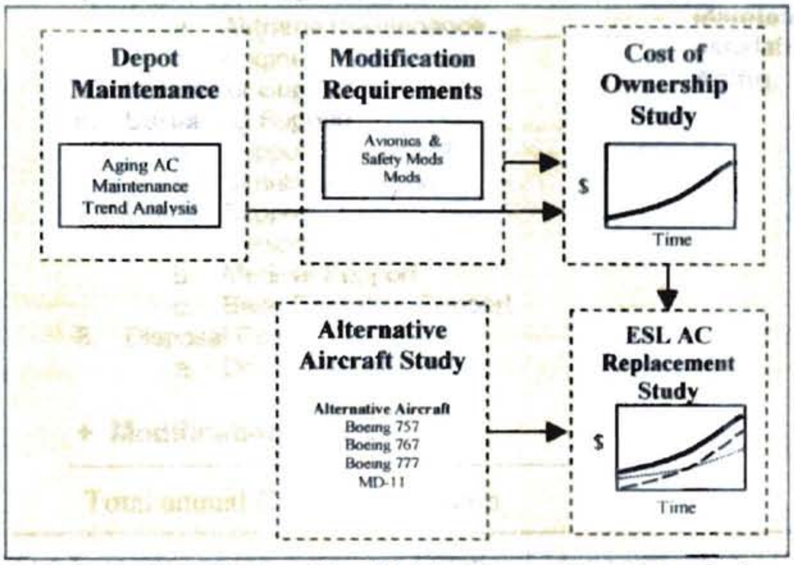


Figure 4. Relationship of Maintenance Trend Analysis Study to Cost of Ownership Study and Ultimate Economic Service Life Study.

A useful LCC analysis format developed by the A.F. Cost Analysis Improvement Group (CAIG) breaks down Operation and Support (O&S) costs in the following hierarchical format. These O&S costs are then be added to forecast modification costs to obtain a total cost of ownership forecast.

When costs are displayed in this logical hierarchical format is now possible to tailor a cost breakdown structure which would account for aging airframe costs (Figure 5).

CAIG Format

O&S Costs

1. Personnel
    a. Aircrew
    b. Maintenance
2. Unit Level Consumption
    a. Fuel
    b. Repairable parts
    c. Consumable parts
3. Intermediate Level Maintenance
4. Depot Level Maintenance
    a. Airframe maintenance ← **Airframe Maintenance escalation due to Aging.**
    b. Engine maintenance
5. Contractor Support
6. Sustaining Support
    a. Support Equipment
    b. Simulator Support
7. Indirect Support
    a. Personnel Support
    b. Medical Support
    c. Base Operating Support
8. Disposal Costs
    a. De-militarization

+ Modification Costs

Total annual Cost of Ownership

Figure 5. The Secretary of the Air Force Financial Management (SAF/FM) Cost Analysis Improvement Group (Caig) Has Documented a Useful Structure to Analyze O&S costs. Aging Airframe Maintenance Costs Should Be Estimated under Section 4a. Depot Airframe Maintenance.

Costs produced by the above structure are in terms of "annual" support costs. These costs would then be repeated for each subsequent year and summed to provide a *cumulative* LCC. Current cost estimating methodology, which does not provide guidance as to how, or to what magnitude airframe maintenance costs may increase can produce significant error.

Figure 6 represents how a cost forecast without aging airframe considerations may quickly accumulate error in a multi-year cost forecast.

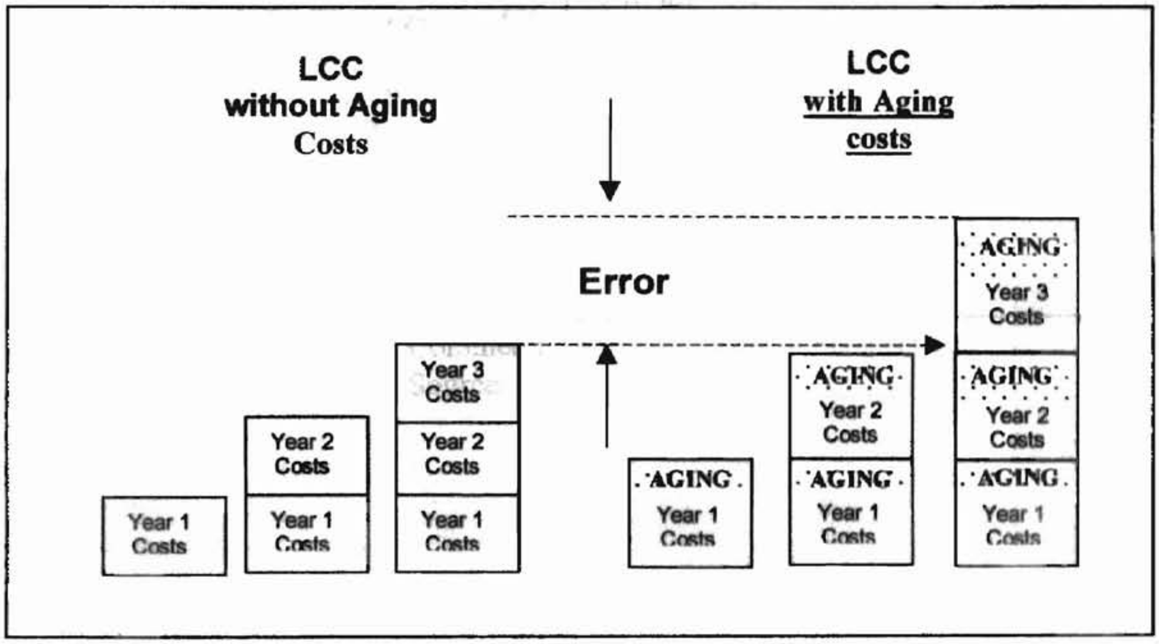
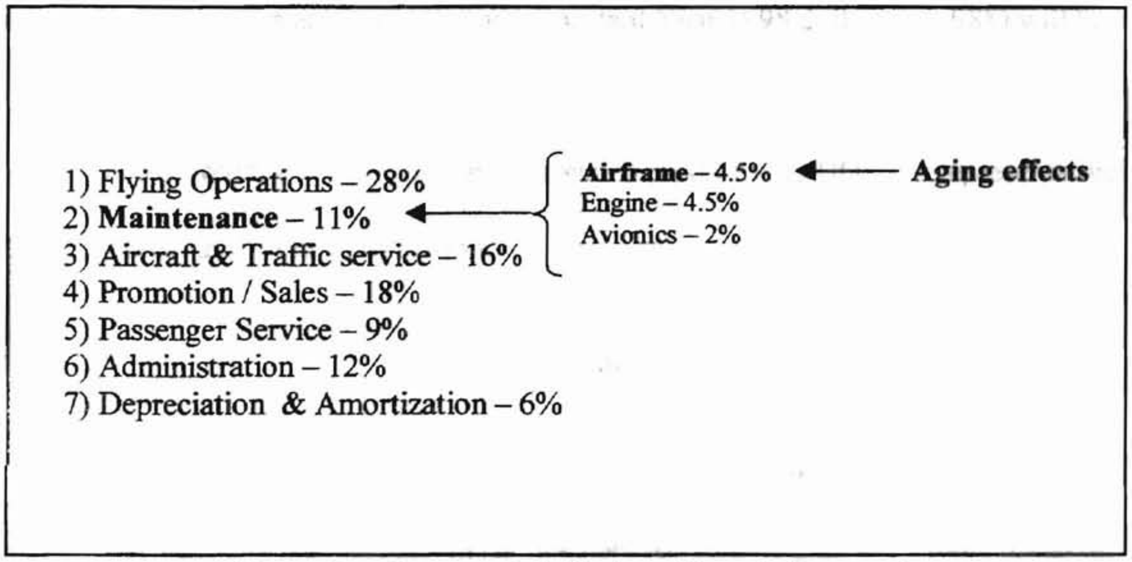


Figure 6. Cost Forecasting Without Considering Aging Maintenance Cost Escalation Can Result in Significant Cumulative Error in LCC Analysis.

To insure we estimate aging maintenance cost growth in perspective, a typical airline's cost categories and relative proportions are presented below (Figure 7). Airframe maintenance costs are typically less than 5% of the total airline operational costs.


1) Flying Operations – 28%
2) **Maintenance** – 11%
3) Aircraft & Traffic service – 16%
4) Promotion / Sales – 18%
5) Passenger Service – 9%
6) Administration – 12%
7) Depreciation & Amortization – 6%

Airframe – 4.5%
Engine – 4.5%
Avionics – 2%

Aging effects

Figure 7. Commercial Airplane Costs in Perspective.
Source: Kane.

The cost forecast is then used as the baseline for comparison against competing alternative. Results from a COO study are then used as the baseline for a ESL study to determine if an aircraft is approaching the end of its economic life. If an alternate aircraft appears viable, an Analysis of Alternatives (AoA) would then be accomplished to select the most appropriate replacement aircraft.

Ground Rules and Assumptions of the Study

This study will review Department of Transportation (DOT) Form 41 data from 1974 through 1998 provided in the Then-Year dollars (TY) and converted to 1998 Base Year dollars (BY) using sector specific AAIA airframe maintenance cost deflators. This conversion is necessary to insure measured year-to-year cost variations are the effect of airframe cost variations and not inflation. Constant Year 1998 dollars (CY98$) will be used within this study.

It is believed the commercial aircraft which report to the DOT are representative of the general aging aircraft population.

Scope and Limitations

This study analyzes fleet-wide airframe maintenance data from aging commercial aircraft. The fleet average has been in service between twenty and thirty years based on production start times for each model analyzed. Airframe maintenance growth trends from this study cannot be directly applied to military aircraft due to the significantly higher commercial utilization.

The classic aircraft studied were constructed from aluminum alloys popular twenty to thirty years ago such as 7075-T6, 7079-T6 and 7178-T6 which have poor corrosion and Stress Corrosion Cracking (SCC) resistance properties. New aircraft are constructed from materials such as 7050, 7150 or 7055 alloys, whose exfoliation-resistant tempers exhibit both corrosion and stress corrosion cracking resistance (NRC 1998). Applications of aging airframe growth rates are therefore limited to aircraft constructed with similar materials and construction techniques. This concept of insuring similar period materials therefore excludes broad-brush application to modern aircraft, which tend to use composites extensively.

Commercial airlines also typically have an ongoing fleet modernization program, constantly tailoring their fleet mix to present day flight routes and load factors. This selective retention also tends to reduce overall fleet mix costs. This is a luxury the military is unable to match as they typically must maintain a fleet size specified by a higher command. Commercial airframe maintenance growth trends would tend to be lower than their military counterparts due to both their ongoing fleet modernization and selective retention.

Basing locations for commercial aircraft also consider the relative environmental effects on aircraft when deciding where aircraft are to be based. Again, the military cannot be as selective due to military basing requirements.

Fleet utilization is also a significant discriminator. Military Tanker / Transport aircraft may average 300 – 800 annual flying hours, whereas their commercial counterpart may average 3,500 flying hours annually. For aging considerations where corrosion is the predominant consideration utilization is not a concern. However, on aircraft with high cyclic fatigue, adjustments would be necessary to insure comparability.

Many of the aging aircraft represented in this study were from an era which did not initially apply corrosion preventative compounds (CPC) during the manufacturing process. Aircraft which remain in commercial service, however, must comply with the intent of Airworthiness Directive (AD91-07-19) which requires the inspection and continued application of CPC compounds during scheduled heavy maintenance checks. Assessing the effectiveness of CPCs applied after the manufacturing process is difficult. Effectiveness is very dependent on compound penetration into tight crevices such as lap joints. CPC effectiveness is also dependent on how well any existing corrosion was removed prior to CPC application. Additionally, due to the newness of the Airworthiness Directive (AD) driven CPC program, many aircraft are only now returning for their second heavy maintenance check since initial application of CPC. Measuring the effectiveness of the CPC program will take several repeat heavy maintenance visits.

Definitions

Analysis – Decision making context involving time horizons extending into the future. A concrete set of specifications are not usually available. There could be many major uncertainties, and a wide range of alternatives, each having several configurations. Analysis is usually concerned with new equipment proposals and new methods of operation of systems never produced before. Analysis Objectives are to find significant differences in resource requirements among alternatives; and, how will resource requirements for any alternative change as key configuration characteristics vary over their relevant ranges. It is often a "sensitivity" type of investigation.

Analysis (NES Dictionary) – A systematic approach to problem solving. Complex problems are simplified by separating them into more understandable elements.

Benefit Cost Analysis (NES Dictionary) – An analytical approach to solving problems of choice. It requires: a) the definition of objectives; b) identification of alternative ways of achieving each objective; and c) the identification for each objective or alternative which yields the required level of benefits at the lowest cost. It is often referred to as cost-effectiveness analysis when the benefits of the alternatives cannot be quantified in terms of dollars.

Constant Dollars – Computed values which remove the effect of price changes over time (inflation). An estimate is said to be in constant dollars if costs for all work are adjusted to reflect the level of prices of a base year.

Corrosion – Corrosion can occur in a variety of nonexclusive forms, including uniform or general corrosion, crevice (filiform and faying surface) corrosion, intergranular (including exfoliation) corrosion, and stress corrosion cracking (ASM, 1987).

Corrosion Preventative Compounds – Generally these materials are a high molecular weight petroleum product which work by displacing moisture from the potential corrosion cell. CPC has been effective in both delaying the progress of incipient corrosion and in preventing corrosion from forming.

Cost (Fisher) – "Economic costs" are benefits lost. It is for this reason that economic costs are often referred to as "alternative costs" or "opportunity costs." It is in alternatives, it is in foregone opportunities, that the real meaning of "cost" must always be found. The only reason you hesitate to spend a dollar, incidentally, is because of the alternative things that it could buy. Some use the word "cost" when referring to resources. Cost of something is measured by the resources used to attain it. Cost of attaining an objective at some point in time is measured by the resources not available for use in attaining alternative objectives. Costs are a measure of other defense capabilities foregone. Money cost is not necessarily the same as economic cost. "Economic cost" implies the use of resources - manpower, raw materials, etc. Dollars are used merely as a convenient common denominator for aggregating numerous heterogeneous physical quantities into meaningful "packages" for purposes of analysis and decision mating.

Cost (NES Dictionary) – The amount paid or payable for the acquisition of materials, property, or services. In contract and proposal usage, denotes dollars and amounts exclusive of fee or profit. Also used with descriptive adjectives such as "acquisition cost," or "product cost," etc. Although dollars normally are used as the unit of measure, the broad definition of cost equates to economic resources, i.e., manpower, equipment, real facilities, supplies, and all other resources necessary for weapon, project, program, or agency support systems and activities.

Cost Analysis – The primary purpose of cost analysis is comparison - to provide estimates of the comparative or relative costs of competing systems, not to forecast precisely accurate costs suitable for budget administration. In this context consistency of method is just as important, perhaps more so, as accuracy in some absolute sense. In comparing the costs of military systems, we prefer to speak of "cost analysis" rather than "cost estimation," because the identification of the appropriate elements of cost -- the analytical breakdown of many complex interrelated activities and equipment -- is so important a part of the method. Weapon system cost analysis is much more than an estimate of the cost of the weapon itself. Weapon procurement costs may be relatively small compared to other necessary costs, such as base facilities, training of personnel, and operating expenses; and these other costs may vary greatly from system to system.

Cost Effectiveness Analysis (NES Dictionary) – A method for examining alternative means of accomplishing a desired military objective/mission for the purpose of selecting weapons and forces which will provide the greatest military effectiveness for the cost.

Cost Model – An estimating tool consisting of one or more cost estimating relationships, estimating methodologies, or estimating techniques used to predict the cost of a system or one of its lower level elements.

Current Dollars – Level of costs in the year actual cost will be incurred. When prior costs are stated in current dollars, the figures given are the actual amounts paid. When future costs are stated in current dollars, the figures given are the actual amounts expected to be paid including any amount due to future price changes.

Deflators – The de-escalation factors used to adjust current cost/price to an earlier base year for comparison purposes. A deflator is the inverse of an escalator.

Economic Analysis (NES Dictionary) – A systematic approach to a given problem, designed to assist the manager in solving a problem of choice. The full problem is investigated; objectives and alternatives are searched out and compared in light of their benefits and costs through the use of an appropriate analytical framework. Often used to determine the best use of scarce resources.

Fixed Year Dollars – Dollars that have been adjusted for inflation to a specific year.

Historical Data – A term used to describe a set of data reflecting actual cost or past experience of a product or process.

Inflation - An increase in the level of prices for the same item(s). Examples of indices that reflect inflation include Consumer Price Index (CPI), Wholesale Price Index, and Producer Price Index. When prices decline it is called deflation.

Knowledge Base - The repository of knowledge in a computer system or organization. The collection of data, rules, and processes that are used to control a system, especially one using artificial intelligence or expert system methods.

Life Cycle - The stages and process through which hardware or software passes during its development and operational use. The useful life of a system. Its length depends on the nature and volatility of the business, as well as the software development tools used to generate the databases and applications.

Parametric Estimating - A mathematical procedure where product or service descriptors (parameters) and cost algorithms directly yield consistent cost information.

Re-engineering - Process of restructuring and redesigning an operational (or coded) hardware or software system or process in order to make it meet certain style, structure, or performance standards.

Validation - In terms of a cost model, a process used to determine whether the model selected for a particular estimate is a reliable predictor of costs for the type of system being estimated.

CHAPTER II

REVIEW OF THE LITERATURE

This review of literature is organized by relative applicability to Life Cycle Cost modeling of aging aircraft. If viewed graphically, it would begin at the apex representing recent studies which attempt to quantify the aging effects on military and commercial aircraft, broadening quickly to a base of literature which guides the novice cost modeler.

Project Air Force – The Rand Corporation

In May 1997, I had the opportunity to brief Dr. Raymond Pyles of the Rand Corporation who is studying aging aircraft for the USAF. This briefing included my research of the military KC-135 and several civilian commercial aircraft which report annual maintenance costs to the Department of Transportation (DOT). Additionally, I was able to furnish Boeing's recognized heavy maintenance forecast growth trends which was completed in December 1997 by Didonato and Sweers of the Boeing Commercial Aircraft Group (BCAG). Pyles has since published his statement to the Procurement Subcommittee of the House Armed Services Committee recorded on the 24 of February 1999. His research strongly complemented the growth trends suggested by my preliminary work. His approach, however, was more general in nature in that he developed the concept of a growth range, which bounded both my earlier work, and the previous work by BCAG. Pyles termed his upper and lower bounds the best case and worst case in which the maintenance of aging aircraft in the military could expect to operate. Pyles went on to generalize how the future costs of fleet modernization projects, aging material failure mechanisms and part obsolescence may combine in unexpected proportions on aircraft which are being operated 20, 30 or possibly even 40 years beyond their Design Service Objective (DSO). In the worst case scenario, a fleet could experience an "unexpected phenomena which could suddenly jeopardize an entire fleet's flight safety, mission readiness, or support cost, and that an extended time period may be required to design, test and field a replacement aircraft."

Boeing Commercial Aircraft Group

Sweers and Didonato (1997), of Boeing Commercial Aircraft Group (BCAG), presented a technical paper titled The Economic Considerations of Operating Post Production Aircraft Beyond Their Design Service Objective at the Aging Aircraft Maintenance and Upgrades Conference in December of 1997. Sweers posed a very useful analogy for attempting to model the costs of aging aircraft. He compared the health care cost of aging humans, to that of aircraft. Typically, how someone took care of themselves during their first 60 years must be known, i.e., to what extent did they stick to a healthy diet, exercise or avoid stress? Also, did they develop any life shortening health habits such as smoking, drinking, or drugs? Were they exposed to toxins or radiation? Did they experience high periods of stress in their lives over a long period? Likewise, one must consider the unique history of each aircraft to develop a meaningful forecast.

Sweers also explained how the Corrosion Prevention and Control Programs (CPCP) compounded the vicious cycle of corrosion and fatigue damage. Aging program directives required the inspection and removal of all corrosion. During the removal process, metal is removed which makes a structure less tolerant of cyclic fatigue. Sweers then developed a forecast heavy maintenance growth curve for the Boeing 727, 737 and 747 as well as the Douglas DC-9 and DC-10.

Khemaies (1999), from International Air Transport Association (IATA), recognized the value of collecting accurate aircraft maintenance costs. In his article Standardizing Airline Maintenance Comparison, he described several pit falls cost analysts studying historical data may encounter. Khemaies cautioned that the mandatory nature of the DOT Form 41 reporting system insures a very large sample size. It does not, however, insure reporting consistency between airlines. One airline may calculate the direct maintenance burden (overhead) for a specific operation, while another airline may assign a direct cost, of 80 percent to account for overhead. Additional reporting discrepancies between airlines may also be due to the apportionment of material handling, support equipment and initial spares provisioning. One airline may account for it as being maintenance related another might account for it as part of the initial aircraft capital costs.

These inconsistencies between airlines could cause significant error for one attempting to compare airline to airline costs. This study however is comparing like aircraft maintenance costs from several airlines over a period of 25 years. Khemaies is working to standardize the DOT data collection system and his international system referred to as the Product Performance Measurement (PPM) are comparable tools useful to evaluate aircraft on a global scale.

Lincoln and Melliere (1998) published a study titled Economic Life Determination for Military Aircraft. This study provided a methodology for using a Weibull distribution of an equivalent initial flaw size (EIFS) in a structural member to predict crack growth rates due to fatigue. Their study also recognized the combining and even compounding effects of Stress Corrosion Cracking (SCC) and Corrosion. Lincoln also emphasized the concept that determining the Economic Service Life of an aircraft is beyond the realm of the structural engineer. The engineer may determine the economics of a single repair but is not positioned to determine when the cumulative economic burden is unacceptable. The concept of total aircraft economics envelops significantly more economic factors than structural repair. It is a secondary purpose of this study to combine the key cost elements which must be considered in an Economic Service Life Study.

Life Cycle Costing by Dhillon (1989) and Life-Cycle-Cost and Economic Analysis by Blanchard (1991) both offer the well known "bathtub curve" used to represent failure behavior of many mechanical and electrical items. This curve represents increasing reliability (decreasing failures) during a component's early life stages, a mid-life period in which the failures are purely random or stable and a third phase which is marked by an upward trend in failures as a function of wearout. Dillon discusses several common aircraft industry LCC models; PRICE (Program Review of Information for Cost and Evaluation), LCOM (Logistics Composite Model), CACE (Cost Analysis Cost Estimating) and BACE (Budgeting Annual Cost) model however, none of these models attempts to quantify the third (or aging) phase of an aircraft life. Another common LCC model used by the USAF is CORE model (Cost Oriented Resource Estimating) model. CORE has gained popularity in recent years due to the AF's interest in lowering costs. The AF has created a Reduction of Total Ownership Cost (R-TOC) program office which has developed several in-depth cost visibility reports, which allow users to trace detailed costs.

The R-TOC program is described very well in a report by Booth in her article What is Total Ownership Costs and Why Should I Care published in the spring 2000 Logistics Spectrum Quarterly. Booth describes the R-TOC goal as insuring costs are not merely pushed from one cost account to another, but indeed tracked, to insure the total cost to the AF is reduced. The majority of RTOC cost reports are furnished in CAIG (Cost Analysis Improvement Group) format. This format breaks down aircraft Operation and Support costs (O&S) into seven major cost elements. These seven costs elements correspond directly with the CORE model's output. This has been the primary cause for the increase in CORE popularity.

In 1997 Lincoln, along with a long and distinguished list of scientists and engineers working for the National Research Council, published a report for the USAF titled Aging of U.S. Air Force Aircraft. In this report, one recurring theme is apparent, the need for an overall economic service life estimation model that integrates the estimates of structural deterioration caused by fatigue, corrosion, and stress corrosion cracking (SCC) with all other operating cost elements. The current lack of such a tool inhibits Air Force planners from establishing a realistic time table to phase out a current system and begin planning for replacement aircraft.

These three basic components of airframe structural deterioration (fatigue, SCC and corrosion) are the same components, which contribute to commercial airframe maintenance growth. It is the purpose of this study to a) validate this suspected growth does indeed exist, and b) measure the annual growth.

Economics and Readiness

The economic burden associated with the inspection and repair of fatigue cracks can be expected to increase with age until the task of maintaining aircraft safety could become so overwhelming and the aircraft availability so poor that the continued operation of the aircraft is no longer viable. In addition, corrosion detection, repair, and component replacement can add significantly to or, in some cases, dominate the total structural maintenance burden.

The committee concludes that the major emphasis of the Air Force's technical and force management with regard to corrosion and stress corrosion cracking (SCC) should be focused on the early detection of corrosion and the implementation of effective corrosion control and mitigation practices so as to drastically reduce unscheduled repairs and replacement costs and aircraft downtime. Key technical issues and operational needs include

- the development of improved NDE techniques for the detection and rough quantification of hidden corrosion;
- the classification of corrosion severity to provide guidance for maintenance;

- the generalized application of corrosion-preventive compounds and the development of corrosion-preventive compounds that can be applied on external surfaces to potect unsealed joints and fasteners;
- the development of a material and process substitution handbook and engineering guidelines for the replacement of components exhibiting corrosion and SCC with more-resistant materials and processes;
- the development and application of materials and processes to inhibit SCC;
- the development of technologies for the removal, surface preparation, and reapplication of surface finishes with improved corrosion-resistant finishes on existing aircraft; and,
- the assessment of the potential use of the dehumidified storage of aircraft, where practical.

The committee believes that fatigue cracking will occur eventually on all aging aircraft as flight hours increase. From an economic standpoint, the major impact for a fail-safe-designed structure occurs with the onset of WFD. For safe-crack-growth-designed structures, the major impact occurs when the structure exhibits a rapid increase in the number of fracture-critical areas. In both cases, a choice must be made to undertake major modifications, structural replacement, or retirement. Although it may not be possible to avoid reaching this point for any given aircraft, operational changes such as fuel management, gust avoidance, active or passive load alleviation systems, reduced pressurization, and flight restrictions to minimize flight in severe mission segments can reduce the rate of fatigue damage and delay expensive repair-replace-retire decisions. For aircraft that are approaching their economic service limit, these options should be considered to allow time for modification or replacement acquisition programs.

Force Management and Predicted Economic Service Life

The Air Force modernization planning process includes the essential elements for force structure planning and management, but, to be completely effective, it should significantly improve estimates of the probable economic service life of aging aircraft systems. There is no clear definition of all of the cost elements that contribute to the economic service life of an aircraft, nor is there a precise methodology for estimating when the costs of operating and maintaining a system will be high enough to warrant replacement. The committee believes that the development of an estimate of economic service life with metrics that integrate the effects of structural deterioration (i.e., from fatigue and corrosion) with economic considerations is essential to force management.

Nelson of the RAND Corporation produced an interesting study in 1997 titled Life-Cycle Analysis if Aircraft Turbine Engines. This study, of course, focused on jet engines rather than airframe costs, but he developed a cost forecasting methodology based on an engines time-of-arrival (TOA). TOA was a useful predictor because it considered the state of the technology at the time of design and manufacture. TOA was one of many predictive factors, others included thrust to weight ratio and developmental costs. The technology, which constitutes the majority of today's aging aircraft, is of a homogenous pool. It is suspected that airframe maintenance will also be influenced by the airframe's TOA.

Predicting aircraft damage due to corrosion and corrosion fatigue crack growth has been attempted by Harlow (1998). Harlow working with the Department of Mechanical Engineering and Mechanics at Lehigh University has developed a mechanistically based probability model. His report Probability Modeling and Analysis of J-STARS Tear-Down Data from Two B707 Aircraft describes his probabilistic approach. Their prediction model is based on damage values, statistically estimated from experimental data for the localized corrosion and fatigue crack growth rates adjusted for primary cyclic loading (flight cycles). The predicted probability of occurrence (PoO) was compared against the multiple hole-wall crack data collected from the inspection of numerous fastener holes on the lowers wing panels of two aging Boeing 707 aircraft. The aging aircraft inspected were part of the USAF military conversion of multiple retired commercial Boeing 707 aircraft into E-8C Joint Surveillance Target and Attack Radar System (J-STARS) aircraft. The two transport aircraft had been in commercial service for 18 and 25 years. One aircraft was a Boeing model 707-123 (s/n #17635, line # 15) had accumulated 78,416 flight hours and 36,359 flight cycles. This aircraft was the highest time –100 series aircraft in service. The other aircraft was a Boeing 707-321B, which had been in service 18 years and accumulated 57,383 flight hours and 22,533 flight cycles. Likewise this aircraft was the highest time –300 model Boeing 707 in service. The model forecast was in very good agreement in predicting damage on the lower wing skins. Predicting damage on the corresponding stiffeners produced less correlation for a variety of reasons; primarily the model uses characteristics of 2024-T3 compared to the actual stiffener material of 7075-T6. Also the stiffeners are thicker than the skins which change their damage tolerance resistance. Harlow's proposed mechanistically based probability model for corrosion and corrosion fatigue cracking appear to have great promise as an effective tool in airworthiness assessment and fleet management. These methods once perfected could be coupled with cost modules to predict and price the cost of maintaining an aging fleet.

Duuette, (1997) unveiled the Federal Aviation Administration's response to the White House's Commission on Aviation Safety in a Press release October 1 1998. The FAA recommends expanding the joint FAA / industry Aging Aircraft programs, which have previously focused on structures, to now cover wiring, hydraulic lines, control cables and pneumatic devices. The Aging Aircraft program was established after the Aloha Airlines accident in 1988. The challenge is to develop maintenance and inspection practices for aircraft systems that adequately address aging aircraft components. As airplanes age, the requirements for inspections, repairs and parts replacement change, and many times increase. This is compounded by the fact the each transport model has a system design requiring maintenance and inspections unique to that aircraft. Much of the new information on the state of aging systems has come to light over the last several years. Information from accident and incident databases needs to analyzed to identify trends in aging systems. The FAA thus far has concluded that wiring is extremely difficult to inspect and there is in many instances insufficient inspection criteria for corrosion on flight control and hydraulic components. The FAA has released a seven step plan enhance the safety of non-structural aircraft components.

1. Establish a joint FAA/industry task team to evaluate the service histories and bulletins for each aircraft model.

2. The FAA will instruct inspectors to scrutinize wiring maintenance, specifically examinations of aging wiring and contamination of wiring.
3. Add aging systems to the FAA research programs, fund research into developing new wire inspection technologies.
4. Improve maintenance data collection involving wiring failures.
5. The FAA is considering regulation which will require aircraft manufacturers to conduct a critical design review to determine if any additional maintenance practices are required to insure fuel tank wiring safety of aging aircraft.
6. Improve wiring installation drawings and wiring installation and inspection instructions, and
7. Establish an Aging Transport Systems Advisory Committee to coordinate the plans and initiatives. This advisory committee will also coordinate with the regulatory agency to mandate corrective actions through the use of Airworthiness Directives (ADs). The addition of non-structural components to the FAA Aging Systems Program will undoubtedly have a corresponding increase in maintenance costs.

Spare parts for aging aircraft are also faced with escalating costs. Moog and Hayes of the Royal Australian Air Force (RAAF) were faced with a unique aging aircraft problem when the USAF decided to retire the F-111 fighter aircraft. In their study 1998 study Aged Aircraft Life of Time Spares Purchase Risk Management they describe how the RAAF has operated the F-111 for 25 years in partnership with the USAF. The RAAF had planned to continue to operate this aircraft for another 20 years until the USAF's decision significantly complicated the logistics support environment of the aircraft. Many parts did become available at significantly reduced costs as the USAF reduced inventory, however due to fiscal budget and warehouse space constraints all of those opportunities could not be realized. Additionally, the RAAF spares management was faced with the paradigm shift of repairable parts becoming throwaway - due to both reduced spares cost and the lack of a repair source, and once throwaway parts now becoming repairable due to the lack of a manufacturing facility. The RAAF now had to define future escalation costs considering the probability of: part availability and production lead-time. While USAF's decision to retire their F-111s has provided the opportunity to purchase large numbers of excess spares at favorable rates, the reduction in maintenance support and the increased storage requirements, may cause a large rise in overall support costs.

Das (1999),of the Boeing Commercial Airplane Group, has studied the economics of consolidating aging aircraft maintenance requirements into an airlines routine maintenance program. The primary interest is to consolidate existing routine maintenance programs with the FAA mandated Corrosion Prevention and Control Program (CPCP) and the fatigue related inspections like the Supplemental Structural Inspection Program (SSIP) under the umbrella of ATA owned MSG-3 rev.2 analysis.

In the current competitive environment airlines must integrate their maintenance to optimize their maintenance resources. Actual time for inspection can often be less then 20 percent of the total cost. Thus, if several inspections are scheduled at the same time when the area is accessed to conduct one type of inspection considerable expenses can be saved. This process typically involves performing some maintenance early to achieve access economy with other mandatory maintenance. Even with the performance of some maintenance early, or out of cycle, the total cost to the operator is often reduced.

Mann (1996) reported that airlines are continuing to operate airplanes in-service longer, pushing the median age of removal from service to past 30 years. Of the planes delivered in 1961 only about 50% were still in service at year-end 1981 (i.e. ~ 20 years of service). However for the airplanes delivered in 1966 about 60% were still in service at year end-1995 (i.e. ~ 30 years of service). He concluded that all data indicates that operators are over-running the airframe manufactures design service objectives on all parameters when measured either in flight cycles, flight hours, and total years of operation. The structural consequences of these actions are decreased inspection intervals, and removal and replacement of certified safe-life parts (mostly landing gear). Operators will continue to deal with more and more corrosion and fatigue damage. Of the 856, Boeing 707s delivered from 1958 through 1994, 384 remain in-service at year end 1995. The bulk of these commercial deliveries ended in 1974, however the Boeing 707 remained in production for mostly military applications until 1994. None of these aircraft are in U.S. registered commercial service. The only older commercial jet transport still reported by the "World Jet Airplane Inventory" is the "Comet 4" of which 75 were produced and one aircraft remains in service at years end 1995.

Johnson (1999), of Ogden Air Logistics Center working with the Aircraft Structural Integrity Program (ASIP) office, has developed a software tool called FLEETLIFE. This software tool is designed to automate the maintenance data collection and trend analysis tasks involved with maintaining aging aircraft. As an engineering tool, FLEETLIFE is designed to provide a means to effectively evaluate annual fleet usage data, structural safety and performance, and overall fleet integrity. The goal is to allow timely management and detect potential negative trends, and pro-actively make corrections to insure future structural integrity of the fleet. Johnson is developing modules that will interface with the Air Force Total Cost of Ownership program office to add the new dimension cost as a fleet performance indicator. A logical next step in the evolution of this tool would be to introduce the capability of cost forecasting based on historical trends.

FLEETLIFE was designed to solve several problems typically found with aging aircraft programs. The foremost problem involves collecting and organizing and analyzing tremendous amounts of maintenance, data associated with a fleet of aircraft. These data are used on a continual basis to assess the current structural health of the fleet,. The problem with most PC based analysis tools is that the source data necessary to accomplish these tasks are usually stored on several disjointed computer systems.

FLEETLIFE's strength is in its ability to communicate with multiple electronics data sources compiling and integrating maintenance and operational data for a accurate fleet health check.

The General Accounting Office (GAO) studied the problem of the aging USAF Air Refueling KC-135 in 1996. The GAO concluded that the long-term supportability of the KC-135 tanker is indeed questionable. Cost per flying hour is projected to increase from $8,662 in 1996 to $10,761 in 2001. Additionally, they sited concern with the increasing depot maintenance downtime, which increased from 158 days in 1990 to 245 days in 1996. Since the GAO report was issued the depot maintenance downtime has increased to 440 days in 2000.

The GAO's primary concern is that the military has little or no experience operating and maintaining aircraft of this age, and there are no commercial airline fleets of a comparable age. Consequently, the Air Force only recently began to study the problem and attempt to predict how long or effectively these aircraft can continue to operate. As the KC-135 tankers age, they require more maintenance, which causes fewer aircraft available for operations. Depot maintenance workload has increased continuously since the aircraft entered its aging phase (about 20 years ago). Depot maintenance man-hours per aircraft have been increasing at approximately 10% annually for the last 10 years in the core depot tasks, and 13% annually if the additional "one-time" maintenance task are included. Air Force officials have started several proactive rejuvenation programs, which currently increase workload but ideally should return significant benefits. Current depot work includes time to apply corrosion preventive compounds (CPC) and rewire significant portions of each aircraft. In addition, shortages of spare parts, that are no longer in production or stocked, and unplanned work, required to correct structural corrosion and fatigue, contributed to maintenance delays and have significantly reduced aircraft availability.

The USAF has currently contracted with The Boeing Company to perform an Economic Service Life Study on the KC-135 aircraft. This study will focus on the Economic considerations of operating an aircraft for potentially eighty-years. Costs of aircraft non-availability as well as several priced options to improve availability will be included in the study.

The Air Force Research Laboratories (AFRL) program office located at Wright Patterson AFB has established an aging aircraft program office within the Airframe

Structural Integrity Division focused on aging aircraft problems. The mission of the Structural Integrity (SI) of Aging Aircraft core areas are to develop technologies to extend the structural service life of aircraft and reduce operating and maintenance costs. The SI Division is divided in four primary areas:

1. Predict widespread fatigue damage (WFD), corrosion and fatigue.
2. Develop methods using deterministic and probabilistic analysis to account for the effects of corrosion and widespread fatigue damage.
3. Develop repair designs and analysis tools suitable for transition to the Air Logistics Centers.
4. Develop both prediction and active dampening methods, to stabilize aerodynamic structures.

The AFRL program office is staffed with a highly experienced and technically competent engineering staff.

One option for aging aircraft nearing the end of their structural service life is a major structural rejuvenation known as a Structural Life Extension Program or SLEP. Mitchell (1996) described how the life of an aircraft is dependent upon a number of variables, such as flight profiles, usage rate, environment basing history, and design philosophy. The first two of these (flight profile and usage rate) affect the design life of the aircraft, i.e., the number of expected safe flight hours. It is interesting to note that while the aircraft is in operation, the dynamic factors (fatigue, flutter, vibration) are the responsible parameters for determining the life expectancy. While the aircraft is sitting on the ground, corrosion damage is normally the dominant driver. This is especially true in proximity to the galley, lavatories, and bilge areas. Mitchell describes how the design philosophy of aircraft has evolved over time. Initially there was the Safe-Life Approach. The safe-life approach predicts a replacement time for aircraft component based on cyclic utilization, typically the number of landings or flight hours. The replacement time is based upon the time required for failure, which is obtained from component fatigue tests. In most cases, a component is designed so that the replacement time for that component exceeds the expected service life of the aircraft. Once a component reaches its replacement time, its safe-life is considered to be used up, and the component or entire aircraft is retired. There were, however, two major problems with this method: 1) Cyclic utilization did not consider manufacturing or maintenance induced defects which can abruptly affect a components life, and 2) retirement times were based on very conservative safety factors, consequently many components were retired prematurely.

The second design philosophy is the "Fail-Safe" approach. The fail-safe approach to aircraft fatigue design was developed during the 1960s. The goal of the fail-safe philosophy is to design multiple load path structures, so that if an individual element fails, the remaining structure has sufficient integrity to carry the additional loads The major problem with this however was that this method did not consider the gradual aging degradation, hence both the primary load path and secondary load path aged (weakened) together.

As a result the U.S. Air Force initiated a design philosophy in the early 1970s called Damage Tolerance Analysis. This method was based on a better understanding of fracture mechanics techniques, which defined the fatigue cracks in aircraft structures. This method had both economic and safety advantages over the previous two methods and is the design philosophy in use today.

Several cost estimation methodologies methods should be used during the estimation process. No single methodology is necessarily better than the other, in fact, their strengths and weaknesses are often complimentary to each other. Five cost estimating methods discussed in Boehm's (1997) book Software Engineering Economics are the analogy, bottom-up, top-down, expert judgment, and algorithms (parametrics). These methods are often used in conjunction with each other.

Analogy Method

Estimating by analogy means comparing the proposed project to previously completed similar projects where cost information is known. Actual data from the completed projects are extrapolated to estimate the proposed project. Estimating by analogy can be done either at the system level or the component level.

The main strength of this method is that the estimates are based on actual project data and past experience. Differences between completed projects and the proposed project can accounted for manually

Bottom-Up Method

Bottom-up estimation involves identifying and estimating each individual component separately, then combining the results to produce an estimate of the entire project. It is often difficult to perform a bottom-up estimate early in the life cycle process because the necessary information may not be available. This method is also commonly referred to as the engineering approach.

Top-Down Method

The top-down method of estimation is based on overall characteristics of the project. This method is more applicable to cost estimates when only global properties are known . The top-down method is usually faster, easier to implement and requires minimal project detail.

Expert Judgment Method

Expert judgment involves consulting with subject matter experts to use their experience and understanding of a proposed project to provide an estimate for the cost of the project. The obvious advantage of this method is the expert can factor in differences between past project experiences and requirements of the proposed project.

Parametric or Algorithmic Method

The algorithmic method involves the use of equations to perform cost estimates. The equations are based on research and historical data and use such cost per flying hour, or annual support costs. Advantages of this method include being able to generate repeatable results, easily modifying input data, easily refining and customizing formulas, and better understanding of the overall estimating methods since the formulas can be analyzed

Rice (1999) presented an approach to Economic Service Life modeling at the Third Joint Conference on Aging Aircraft. His primary focus is attempting to model the

USAF KC-135 aircraft. This aircraft is a unique case study in aging aircraft in that the aircraft is over forty years old, yet has accumulated the flying hours equivalent to a five year old commercial aircraft. Growing maintenance and repair costs for the KC-135 fleet are only weakly dependent on the structural aging of these aircraft relative to their design service goals. The growing problem appears to due to "environmental aging", as compared to "structural aging". Additional depot maintenance downtime has caused a significant reduction of aircraft available to for operational service.

The Programmed Depot Maintenance (PDM) trends for the fleet of KC-135 aircraft has continued to increase causing a continued reduction of available (Figure 8).

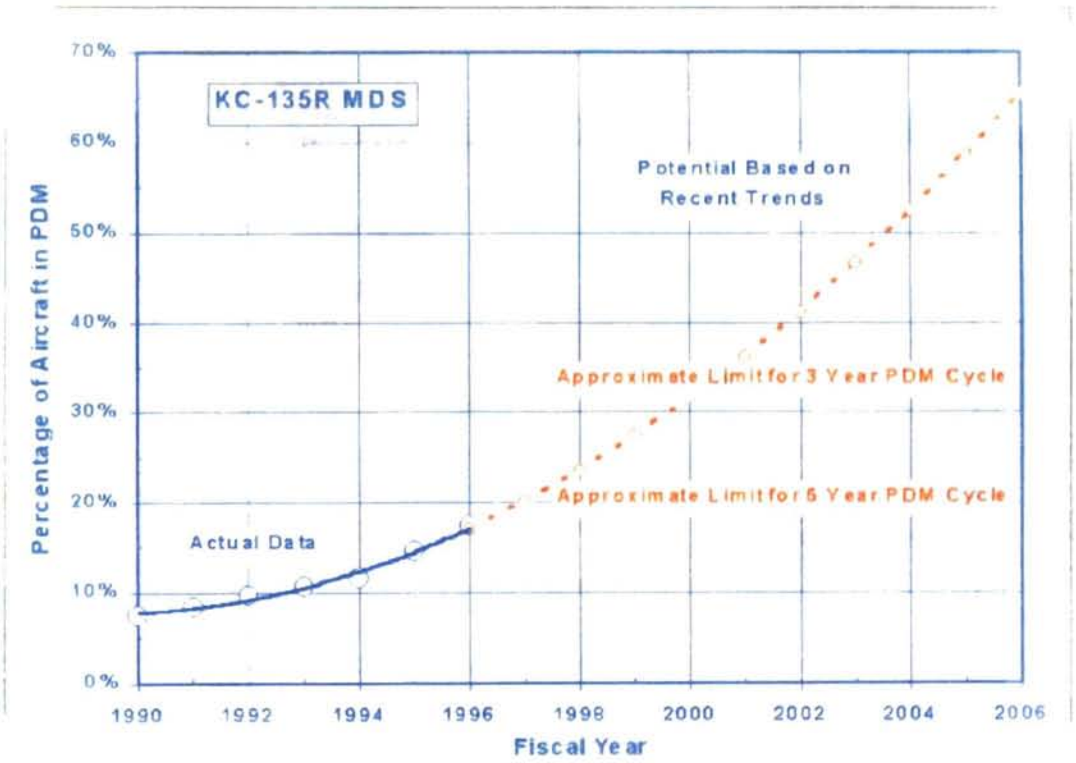


Figure 8. Aircraft Available for Operational Missions are Reduced by Approximately 30% Due to Increasing PDM Downtime. Source: Rice.

The military has also considered increasing the PDM cycle from 5 years to 8 years intervals in the near future to make more aircraft available for operational missions.

Rice suspects the increasing workload is due primarily to corrosion since the aircraft have accumulated so little flying time (Figure 9). His presentation also included an introduction to the work performed by Abbot of the Battelle Corp. For the past 5 years Abbott at Battelle has been collecting corrosion growth rate data from a large number of field sites around the world. This work has been done in support of military research for the USAF. These corrosion monitors include a variety of unprotected strips of corrosion-susceptible materials.

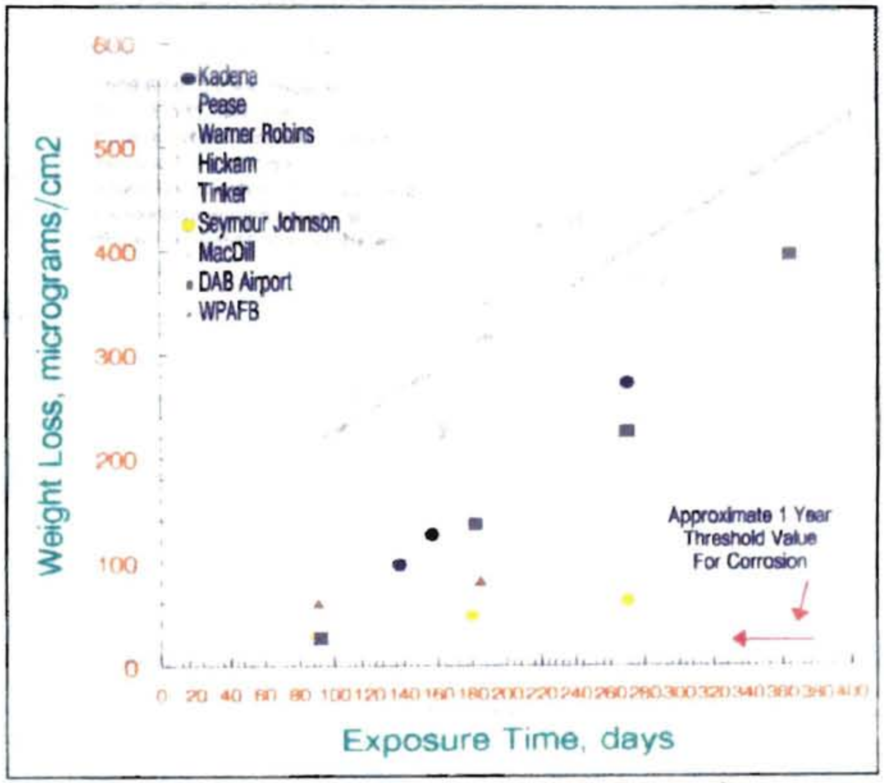


Figure 9. Corrosion Growth Rate of 6061 Aluminum Test Specimen. Source: Rice.

The amount of weight loss for each strips, in terms of micrograms/cm^2/year, is measured at regular intervals. An example of corrosion rate data collected on 6061 strips at several different Air Force bases around the world is given in Figure 10. The weight loss due to corrosion attack has been modest at many sites, but it has been very substantial at other locations. Rates of weight loss on 6061 aluminum samples measured at 41 bases around the world have varied by nearly 2 orders of magnitude; ranging from 8 to 680 micrograms/cm^2/year.

Rice was able to validate this concept of Environmental Severity Index (ESI) by correlating the bases with a high ESI to corrosion related maintenance reported at each

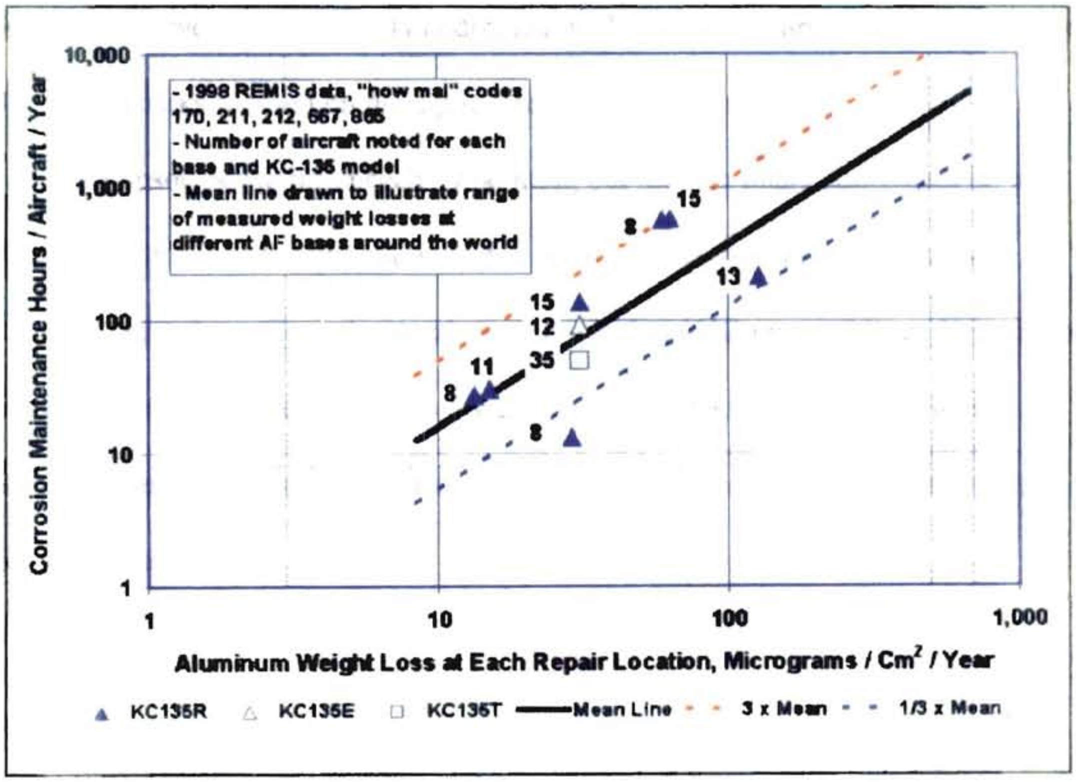


Figure 10. Field Maintenance Data Supports the Corrosion Severity Index as Defined by Abbot. Source: Rice.

location. Organizational level (or field) maintenance data was collected from the USAF Reliability and Maintenance Information System (REMIS) for "how malfunction" codes which described corrosion related damage. Field maintenance data supports the ESI rankings as defined by Abbot. It remains to be seen whether corrosion-related maintenance man-hours during PDM show a similar positive correlation with this indirect measure of base environmental severity.

This area of corrosion related forecasting is a necessary step to predicting future maintenance costs especially for 40-year-old aircraft. On aircraft in this situation it is believed corrosion is the dominant maintenance driver as compared to fatigue related damage.

Thompson, of the Lexington Institute and teacher of the National Security Studies Program at Georgetown University addressed the Military Procurement Subcommittee in 1999. His remarks focused on the aging fleet of military aircraft.

Thompson began his speech by pointing out the fact many Americans do not realize that only 3% of the federal budget is spent on weapons procurement and modernization and we currently spend about twice that (6%) on gambling. He point out in his very effective speech the gamble we are currently taking with our military. At stake here is sending our military personnel to war in obsolete, aging aircraft. Let me begin with a story . . .

An Aging Air Force – L. B. Thompson

Every year the U.S. Air Force holds an "Aerospace Power Demonstration" at Elgin Air Force Base in Florida. I attended in September, and it was really impressive. But let me tell you a little bit about the aircraft displayed on that day.

The first plane that flew over was a KC-135, the most common aerial refueling tanker in the Air Force fleet. It's basically a military version of Boeing's venerable 707 jetliner. The Air Force has over 500 KC-135s in its fleet. On average, they're 38 years old. The KC-135 was refueling a B-52H bomber. B-52s make up over a third of the service's long-range bomber fleet. The average B-52H in the active fleet is 37 years old, and has accumulated over 14,000 hours of flight. But the Air Force plans to keep the planes flying for another 30-40 years.

The next plane the crowd saw was a propeller-driven C-130 refueling helicopters. Like the KC-135 and the B-52, the C-130 was designed in the early 1950s. I don't know what the average age of the Air Force's 500 C-130s are, but I do know this: many of them are so far beyond their planned design life that the Air Force and Navy no longer try to predict when they will need structural repairs; they just wait until cracks appear and then fix them. The helicopters being refueled by the C-130s were MH-53 Pave Low aircraft. The original airframes were produced between 1966 and 1973 – in other words, over a quarter-century ago.

Of course the crowd at the Aerospace Power Demonstration saw some much new aircraft, such as the B-2 Stealth bomber. But the Air Force only bought 21 B-2s and does not expect to get any more new bombers until after the year 2030. Which means the bomber force will keep aging for the next three decades, and can only be kept potent through continuous upgrades of existing aircraft.

The average Air Force plane is now 20 years old, and 40% of the active fleet is at least a quarter-century old. When planes get this old, they start to experience three interrelated types of problems. First, corrosion and fatigue begin to reduce their availability, as more and more time needs to be spent inspecting and repairing them.

Second, the cost of acquiring and installing replacement parts becomes higher and higher because the number of qualified suppliers and maintainers has dwindled and their special skills must often be used inefficiently.

Third, since the technology in the planes is getting older, they and their crews are increasingly likely to be lost in combat.

The end result is that the nation spends more and more money on a less and less capable air fleet. Support costs may not have the budgetary visibility of B-2 production, but year after year they add up. That's one reason why operations and maintenance spending now consumes more of the Pentagon's budget than R&D, procurement, military construction and family housing combined.

In fairness to the Air Fore, it must be said that the service is fielding an excellent replacement for its workhorse C-141 transports, the highly capable C-17 – and just in time, since the average C-141 has accumulated over 38,000 hours of flight time and is subject to flying restrictions due to structural problems.

The Air Force also has a planned replacement for the F-15 fighter, the F-22 Raptor. It's timely too, because the F-15 was designed 30 years ago, before the advent of low-observables technology. The average F-15 is 14 years old today and has used up about half of its 8,000-hour design life. The air-superiority variants fo the F-15 are older, with some of the earlier models in the reserves now exceeding 20 years of age.

Whether the Joint Strike Fighter will materialize as planned to replace the F-16 fighter (average age, 10 years) is anyone's guess. But not all aging aircraft require a new program start. The C-130 airlifter remains a remarkably versatile aircraft. We just can't keep flying the same tired airframes and avionics forever.

<u>Army and Marine Corps Helicopters</u>
Let me turn now to the Army and Marine Corps helicopter inventories, which exhibit many of the same symptoms of advanced age seen in the Air Force.

The Army's top modernization priority is the stealthy RAH-66 Comanche armed reconnaissance helicopter. Comanche's radar reflectivity is less that 1% that of the aircraft it will replace, and its heat and acoustic signatures have been cut in half. Its digital avionics, advanced sensors and other features will allow it to replace the Army's entire fleet of light-attack and scout helicopters with far more effective, maintainable aircraft.

But to say Comanche has been a long time coming would be an understatement. This year marks the 20th anniversary since the Army first formally stated a requirement to replace its Vietnam-era light-attack and scout copters. Since that time, the service's fleet has been growing steadily older.

- *There are about 500 AH-1 Cobra light-attack helicopters in the total Army, and on average they are 29 years old. Army policy sets the useful service life of such combat aircraft at 20 years.*

- *There are also nearly 900 Kiowa OK-58 scout helicopters in the active-duty force and reserves. Most are Vietnam-vintage "A" and "C" variants that lack basic survi8vability features such as self-protection, crashworthiness, tolerance to ballistic damage and chem-bio defense. Average age: 30 years.*
- *Finally, about 40% of the Kiowa fleet are rebuilt aircraft in the more capable "D" configuration with an average age of 9 years. These are much better than earlier Kiowas, but they aren't stealthy, they can't keep up with the Apache heavy attack copters, and they have other limitations.*

The existing inventory of Army light-attack and scout helicopters is obsolete. It requires too much maintenance and support to keep operational, and it delivers too little capability to function effectively in the battlespaces of the next century. But with Comanche not scheduled to become operational until 2006, it's a safe bet much of the current fleet will still be flying in 20 years. The Marine Corps faces a similar problem with aging copters, but the solution to its most pressing needs is already at hand in the form of the V-22 Osprey tilt-rotor aircraft. The Osprey will replace two aircraft.

- *The CH-46E Sea Knight medium-lift helicopter, which has an average age of 30 years and is operating with restrictions on its payload weight and flight regime.*
- *The CH-53D Sea Stallion heavy-lift helicopter, which has an average age of 28 years and costs nearly $4,000 per flight hour, in part because 38 hours of maintenance are required for every hour of flight.*

The V-22 will have much greater range, speed, survivability, and maintainability than the aircraft it replaces (probably around five hours of maintenance per flight hour). The tragedy is that if the Osprey had been kept on its original production schedule, replacement of the CH-46 could have begun in 1991. Now it will be many years into the next century before all 360 Marine Corps V-22s are operational.

Navy Carrier-Based Aircraft

Let me come now, finally, to the Navy's carrier-based aircraft. The Navy operates a diverse collection of fixed-wing aircraft in its eleven carrier air wings to carry out missions ranging from precision strike to electronic warfare to airborne surveillance. Because it is costly and complicated to operate many aircraft types with different logistic tails and maintenance procedures, the service wants streamline its missions and reduce the number of aircraft types to only three or four. But it is proceeding so slowly that age and attrition may catch up with the fleet before solutions are in hand.

The one area where there is not a problem is the strike fighters. The Navy has begun procuring an advanced version of the F/A-18 called the Super

Hornet that will take over the roles of the F-14 fighter, A-6 attack aircraft (already retired), and the earliest variants of the F/A-18. Since more recent versions of the Hornet today average only seven years of age, replacement of other strike assets with the Super Hornet will essentially solve that aging aircraft problem for a generation.

The same cannot be said of the EA-6B jamming aircraft, which is essential to combat support of the strike fighters. With retirement of the Air Force's last EF-111 Raven in May of last year, the EA-6B Prowler is the only dedicated tactical jammer left in the U.S. aircraft inventory. It therefore plays a critical role supporting joint missions in places such as Bosnia and Iraq, particularly in the suppression of enemy air defenses.

But the average Prowler is already over 16 years old, and the production line closed ten years ago. As the chart on the next page indicates, the age of the aircraft will increase continuously through the next decade, while the number of aircraft will fall at the rate of one or two per year due to attrition. At the end of the decade it declines below the minimum number needed to meet global requirements. By that time, the average EA-6B will be 30 years old.

The Navy is putting new wings on the aircraft and installing an advanced electronic-warfare suite, but the simple fact is that the Prowler is getting old. The high rate of current use is wearing it out. If we want to have an alternative ready to go sometime in the next ten years, the Navy must begin planning now for a replacement. Otherwise, age, attrition, and overuse will soon undermine its ability to perform joint electronic-warfare missions.

The various support aircraft on the carriers present a similar aging problem. The Navy presently operates several variants of the E-2 and S-3 airframes for airborne surveillance, signals intelligence, antisubmarine warfare, and other support missions. There are too many aircraft types and some of the missions have become marginal. In addition, the aircraft is ten years old today, and will continue aging despite the production of new aircraft (see chart). The other airframe, the S-3, has not been produced in twenty years, although half the inventory was modified between 1988 and 1990.

The Navy needs to find a common airframe for all of the carrier-based support missions and start planning for its acquisition. But the administration's fiscal year 2000-2005 spending plan contained almost nothing for a so-called "Common Support Aircraft." So this is an aging aircraft problem unlikely to be resolved anytime soon.

> *Conclusion*
> *Whether they are fixed-wing or rotary-wing, land-based or sea-based, the aging aircraft I've discussed today raise serious operational concerns. In some cases, they raise safety concerns. We are now living with the consequences of a decade-long "procurement holiday" – a period of depressed investment that will have unavoidable repercussions for military preparedness in the years ahead. Nowhere is this more apparent than in the nation's aging inventory of military aircraft.*
>
> *Air power should be the cutting edge of American military power. It still is, but that edge is beginning to look distinctly dull and rusty. We have to do a better, faster job of modernizing. Thank you. (Thompson, 1999)*

Thompson's speech (1999) is an excellent summary of the concerns faced by those involved with maintaining "the aging fleet." America's readiness should never be a gamble.

CHAPTER III

PROCEDURES

Maintenance data was collected from the Department Of Transportation Form 41. The DOT and FAA use the Form 41s to monitor financial and operating performance of commercial airlines. It was initially hoped that additional maintenance data from the International Air Traffic Association (IATA) could be obtained and compared as part of this study. Historical data from IATA, however, is closely guarded because many airlines do not want to share specifics about their operating costs.

Data Sources

Data from the commercial airlines was collected by analyzing 25 years (1974 through 1998) of historical DOT Form 41s. All US certified carriers report into the DOT Form 41 data system. By law, each carrier completes a system of uniform accounts and reports according to a set schedule. Individual schedules of the Form 41 are grouped as follows: Section A – Certification, Section B – Balance Sheet Elements, Section P – Profit and Loss Elements and Section T – Traffic and Capacity Elements. The deregulation act of 1978 specified its concern for air service to continue to small communities. Points within the continental United States are to be monitored as essential air service points to ensure their continued service. The requirement to comply with the

Governments need for such statistical and financial data did not dissolve with deregulation, it merely transferred responsibility from the Civil Aeronautics Board to the Department of Transportation.

This DOT reporting system allows for financial and operating performance to be tracked. This data is collected by the DOT who allows commercial electronic data processing companies access to this data. Companies such as; Back Engineering Inc, Airclaims International, Avmark Aviation Services and Aircraft Economics Ltd. process and sell compiled databases to independent market researchers. Data is collated and compiled by air carrier, airplane model, fleet size, flight hours, landings, airframe labor, engine labor, airframe material, engine material, and both direct and indirect costs. The air carrier data used for this study was limited to major U.S. airlines which still operate the "classic" generation Boeing 727, 737, 747s and McDonnell Douglas DC-9 and DC-10s. The airlines that still operate these older aircraft which qualified for this sample were American, American West, Alaska, Continental, Delta, Federal Express, Northwest, TWA, United, USAIR and Southwest Airlines.

Data Collection Process

Twenty-five years of commercial airline maintenance data has been reviewed for trend analysis. This correlational study documents a relationship between airframe maintenance costs and the age of an aircraft. The aircraft studied represent the total population of U.S. registered, out-of-production, heavy commercial aircraft which report costs through the DOT Form 41 system. This population represented more than 1,300 aircraft per year or approximately 32,800 data points over a twenty-five year period.

The type and model of aircraft studied were specifically limited to "out-of-production" models, which still report maintenance to the Department of Transportation. This study does not control for the individual age of each aircraft in the fleet or account for high maintenance aircraft, which are removed from service. This study uses the "as-reported" average fleet maintenance reported by each airline. Assuming each airline exercised prudent internal economic reasoning to control maintenance costs, these reported costs should therefore represent airline industry wide statistics and maintenance trends.

The results of this broad scope study which combine various aircraft operated in various environmental conditions were therefore not greatly influenced by an individual maintenance practice, individual aircraft, individual airline nor basing location. Likewise the results of this study should be applied in similar broad-brush or general fashion, acknowledging that this study documents only general historical trends. The predictive value of this historical trend analysis should therefore be evaluated for each specific application.

Aircraft evaluated for this study were as follows:

- Boeing 727-100C and -200
- Boeing 737-200 and -200C
- Boeing 747-100 and –200
- McDonnell Douglas DC8-71 and -73F
- McDonnell Douglas DC9-10, -30 and -40
- McDonnell Douglas DC10-10 and –30

Commercial airline maintenance cost data from the U.S. Department of Transportation Form 41 reporting system was analyzed for the years 1974 through mid year 1998. The specific cost categories of interest are as follows:

Account Code	Account Name
P52 52251	Total Labor Cost for Airframes
P52 52252	Total Labor Cost for Airplane Engines
P52 52431	Total Cost of Contracted Airframe Repairs
P52 52432	Total Cost of Contracted Airplane Engine Repairs
P52 52461	Total Cost of Airplane Maintenance Materials
P52 52462	Total Cost of Maintenance Materials for Airplane Engine
P52 52780	Total Cost of Direct Maintenance
P52 52796	Total Maintenance Burden
T3 Z510	Total Revenue Airplane Landings
T3 Z650	Total Airplane Flight Hours

Trend analysis was conducted on both airframe labor and airframe material costs. Reported labor costs were converted to maintenance labor man-hours by dividing the reported cost per flying hour by the "Then-Year" (TY) industry standard hourly labor rate for airline mechanic workers as identified by Department of Labor. Airframe maintenance material costs were also analyzed. These costs were converted to constant year 1998 dollars to remove the effects of inflation. As discussed earlier, it is acknowledged that financial reporting differences between airlines exist. Some airlines which "contract-out" maintenance may report their airframe maintenance as airframe material costs and therefore have little to report for airframe labor. To insure these costs were captured, airframe material dollars were also analyzed over this same period.

Ideally, maintenance data from older Boeing 707s could also be collected for this study; however, there are no Boeing 707s in U.S. commercial service; consequently none report to the DOT Form 41 system. Internationally registered commercial 707s do report to an equivalent system maintained by the International Air Transport Association (IATA). Their equivalent maintenance information is published in an annual report titled "Product Performance Measurement" (PPM). Access to the IATA report is restricted, as it provides insight into a specific airline's competitive maintenance programs. Consequently, only three years of nonconsecutive PPM reports were available (1992, 1993 and 1996). In 1992, three operators were reporting 707 activity: Middle East Airlines (MEA), Pakistan International Airlines (PK), and Royal Jordanian Airways (RJ). The total of three years' worth of data collected represented only 15 aircraft. During the 1993 to 1996 data gap, two operators retired their 707s, leaving only Middle East Airlines operating seven Boeing 707 aircraft.

Maintenance data from the IATA PPM reports was inadequate for trend analysis. Air France has been requested to furnish additional PPM reports. However, that additional data has not been received.

Data Manipulation Procedures

Fleet Size Adjustment

To account for the differences in fleet sizes between airlines and insure proportionate representation of each aircraft, a composite cost per flying hour was developed by multiplying the reported cost per flying hour times the number of aircraft the airline possessed that year. The composite cost per flying hour was then summed for all like-model aircraft and divided by the total number of like aircraft reported for that year. The result is a cost per flying hour, which proportionately reflects each airline's individual costs based on their costs as a percentage of total fleet size.

Changes in Fleet Size

Rapid changes in fleet size (both buying and selling of aircraft) can significantly affect maintenance trends. Typically an airline planning to reduce inventory will avoid elective maintenance two or three years prior to selling the aircraft. Elective maintenance is defined as required maintenance, however the FAA may allow several means of compliance. For example an Airworthiness Directive (AD) may require part replacement as the final terminating action. The AD however, may offer an alternate means of compliance such as a repetitive inspection. If an operator is planning on selling the aircraft soon, they most likely will perform the less expensive means of compliance. These two different methods of compliance typically have significantly different financial impact. It is noted that many of the "Aging Airplane Service Bulletin Structural Modification Program" Service Bulletins and subsequent Airworthiness Directives were released in the mid to late 1980s. A marked upturn in reported airframe support costs can be correlated to these additional maintenance requirements.

Planned fleet reduction is recognized as an unrealistic drop in fleet maintenance costs, when in fact the decreases are due to changes in maintenance practices, and not inherent to aircraft design. Often when fleet size is reduced, an overall reduction in maintenance cost is realized by the airline as they selectively retain only the lower maintenance aircraft. To eliminate the false impression that aircraft suddenly cost less to maintain toward the end of their lives, this misleading data has been removed from analysis.

Airframe Maintenance Man-Hour Trend Analysis

The primary metric to be analyzed within this study is airframe maintenance man-hours per flying hour. A longitudinal plot of airframe labor hours per flying hour from 1974 through 1998 will be performed for trend analysis. The actual source database required some manipulation however to be considered useful for analysis. Much of this clean up again was caused by the rapid reduction of fleet size as airlines removed aging aircraft from their inventory.

Airframe Material Dollar Comparison

Two data samples from the reported material costs were also gathered for comparison. Airframe support dollars per flight hours from 1985 and airframe support dollars from 1998 were selected for comparison. In many cases however, the airline had removed all of the subject aircraft by the second sampling period (1998). In those cases data was collected from the oldest reporting period which still reported reliable data prior to the unrealistic decrease experienced immediately prior to selling the remaining fleet. Data selected for analysis for the material comparison is identified by a border around the sample year. These two data samples will be compared using a statistical t-test at a confidence level of .99 ($\propto$ =.01).

Man-Hour Trend Analysis

The process to analyze each of the commercial aircraft data samples was similar. Initially each individual airline's reports were examined to eliminate erroneous trends caused by changes in fleet size. Figure 11 represents the individual airline's reported airframe maintenance costs per flying hour.

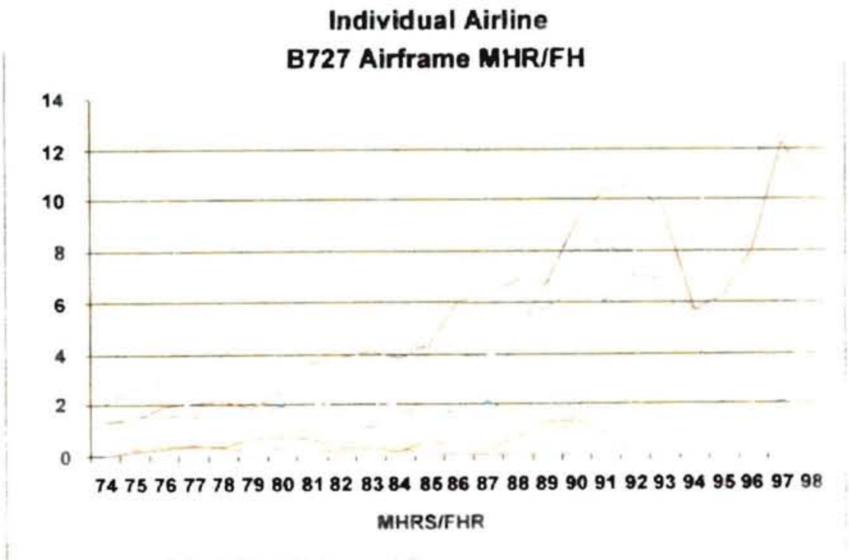


Figure 11. Airframe Maintenance Costs for Each Airframe are Examined. Sample Data Representative of the B727.

Reported airframe maintenance costs per flying hour for each airline were multiplied by the number of aircraft reported by the airline. These products were then summed for all airlines for a given year then divided by the total reported fleet size to produce a weighted fleet average which was representative of airlines with different size fleets of like aircraft. This weighted fleet average was necessary to recognize that one airline may report 10 aircraft with airframe costs of $50 per flight hour and another airline may report 100 aircraft at $90 per flight hour.

Below, Figure 12 identifies the average maintenance man-hour per flight hour for both airframe and power plant. The heavier portion of the line identifies the airframe trend segment of interest. These trend segments typically started after the aircraft fleet was approximately 20 years old and is represented by a steady increase in airframe maintenance.

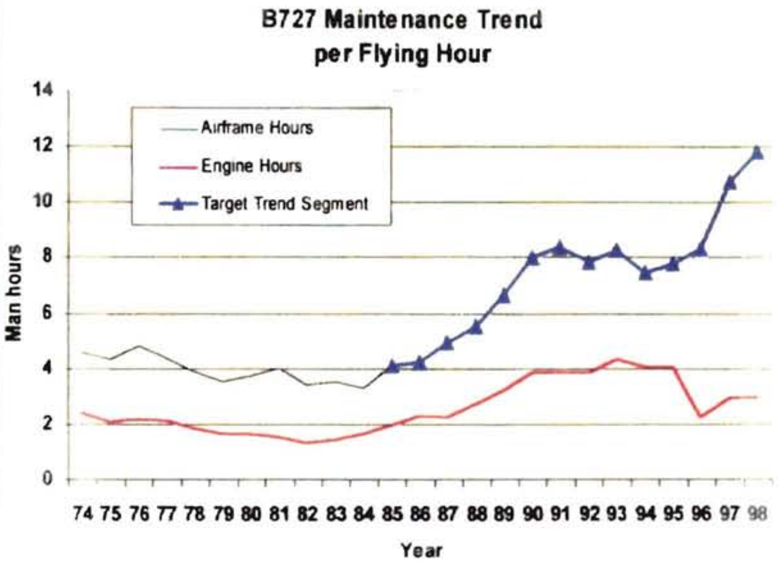


Figure 12. Average Airframe Maintenance Costs are Calculated.

Figure 13 depicts how a typical regression analysis was then performed on the airframe target trend segment. A linear regression trend line has been superimposed over the target segment. Also calculated is the regression equation and coefficient of determination for the trend segment. The linear regression equation was also used to calculate the trends midpoint at the first and last year of the target trend segment. An annual compounding reference growth trend line which starts with the computed value in the first trend year and parallels the regression line is used to describe growth in terms of annual compounding growth.

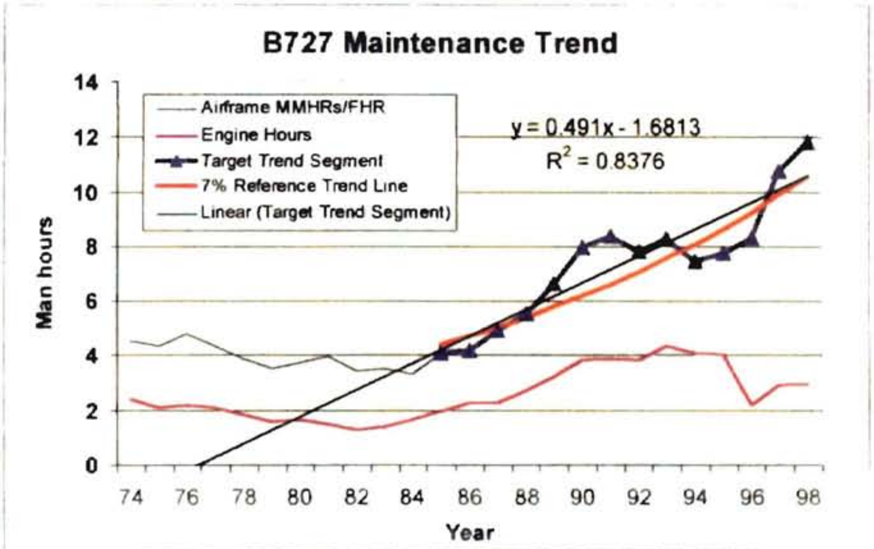


Figure 13. Average Fleet Wide Boeing Classic 727 Maintenance Grew at 7% Annually.

CHAPTER IV

FINDINGS

The Boeing classic 727 was in production for 22 years, from 1960 to 1982 with a current average fleet age of 27 years. An average of 655 aircraft reported each year for 25 years representing a total of 16,375 data points.

Figure 14 presents the upward maintenance man-hour per flying hour trend that started in 1985 and continues today. Figure 14 shows the classic Boeing 727-100 and 200 experiencing approximately a 7% annual growth in airframe maintenance from 1985 though 1998.

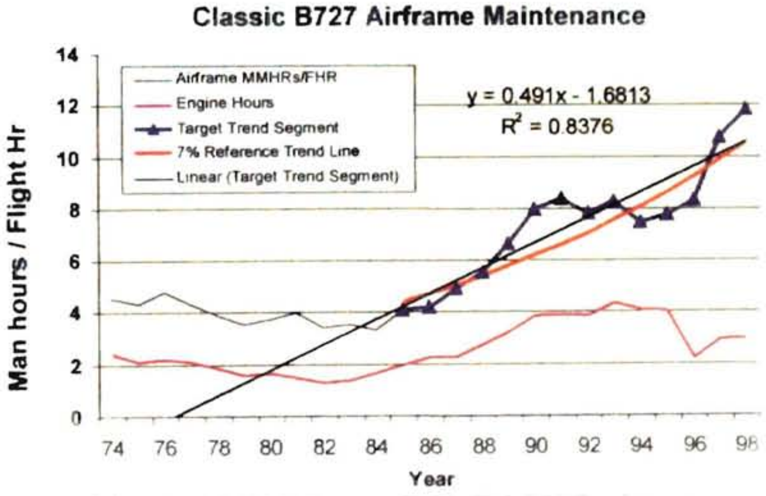


Figure 14. Average Fleet Wide Boeing Classic 727 Maintenance.

The Boeing classic 737-200 was in production for 24 years from 1964 to 1988 with a current average fleet age of approximately 21 years. An average of 210 aircraft reported each year during this twenty-five year period totaling 5,250 data points.

Figure 15 presents the Boeing 737-200s upward airframe fleet maintenance trend which started in 1986 and continues today. Average fleet wide airframe maintenance measured in airframe maintenance man-hours per flying hour appears to be growing at approximately 4% annually.

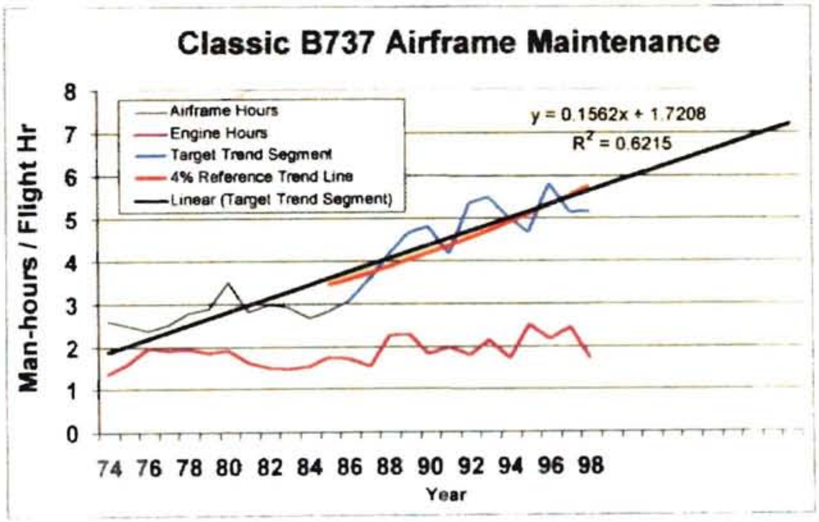


Figure 15. Average Fleet Wide Boeing Classic 737 Maintenance.

The Boeing classic 747-100s and -200s were in production for 21 years from 1970 to 1991 with a present average fleet age of 19 years. An average of 60 aircraft reported each year during this twenty-five year period totaling 1,500 data points.

Figure 16 shows the upward fleet maintenance trend which started in 1986 and continues today. Average fleet wide airframe maintenance on the classic 747-100s and 200s appears to be growing at approximately 7% annually.

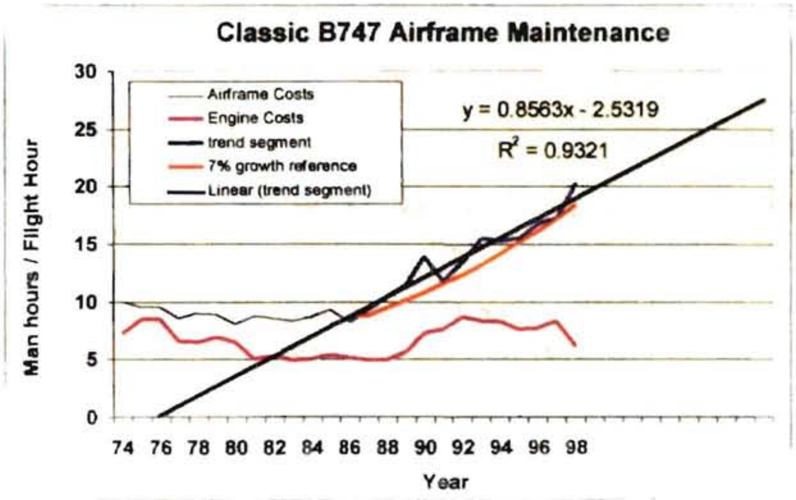


Figure 16. Average Fleet Wide Boeing Classic 747 Maintenance.

Figure 17 describes the DC-8 available data. An average of only 17 DC-8 aircraft per year reported during the 8 year period from 1982 through 1989. This data was statistically insignificant for trend analysis.

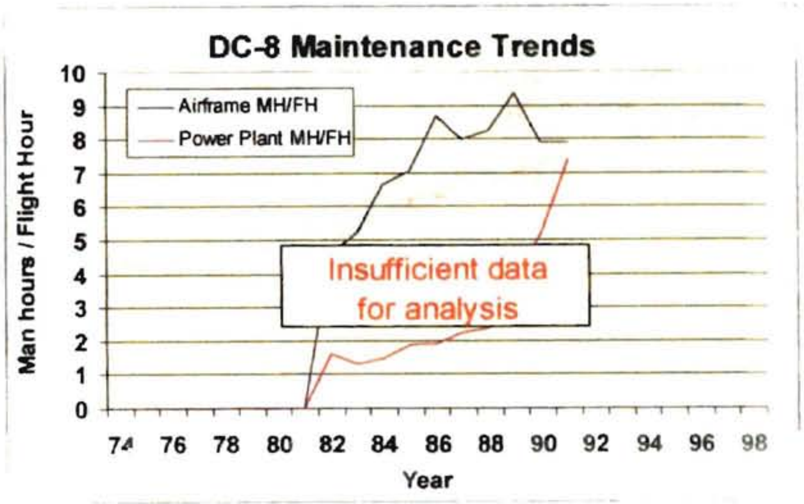


Figure 17. Insufficient Quantity of DC-8s
Report to DOT for Analyis.

The McDonnell Douglas classic DC-9, -10, -30s and –40s were in production for 15 years from 1966 to 1981 with a present average fleet age of approximately 25 years. An average of 275 aircraft reported per year during this twenty-five year period totaling over 6,800 data points.

Figure 18 shows an upward airframe fleet maintenance trend, which started in 1983 and continues today. Fleet wide airframe maintenance on the DC-9 appears to be growing at approximately 3.5% annually.

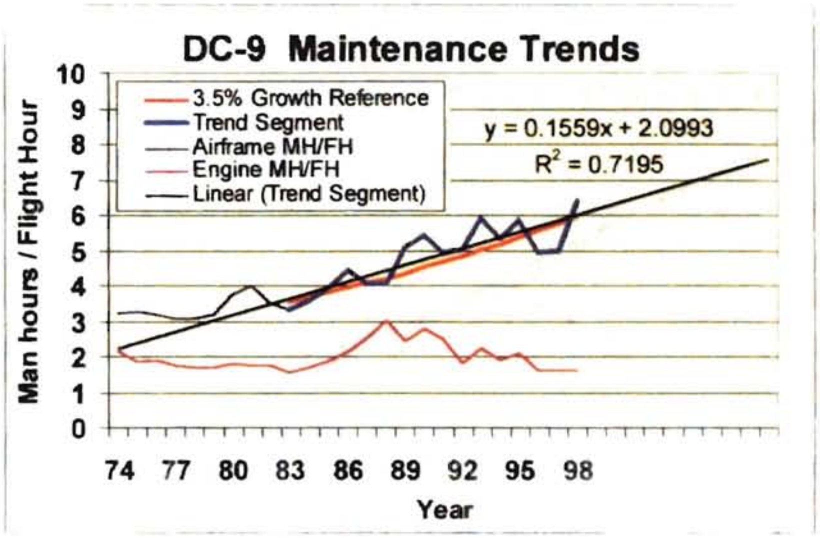


Figure 18. Fleet Wide Airframe Maintenance on DC-9.

The McDonnell Douglas classic DC-10 and -30s were in production for 17 years from 1971 to 1988 with a present average fleet age of approximately 20 years. An average of 115 aircraft reported per year during this twenty-five year period totaling over 2,800 data points.

Figure 19 shows this upward fleet maintenance trend which started in 1983 and continues today. Fleet wide airframe maintenance on the DC-10 appears to be growing at approximately 9 % annually.

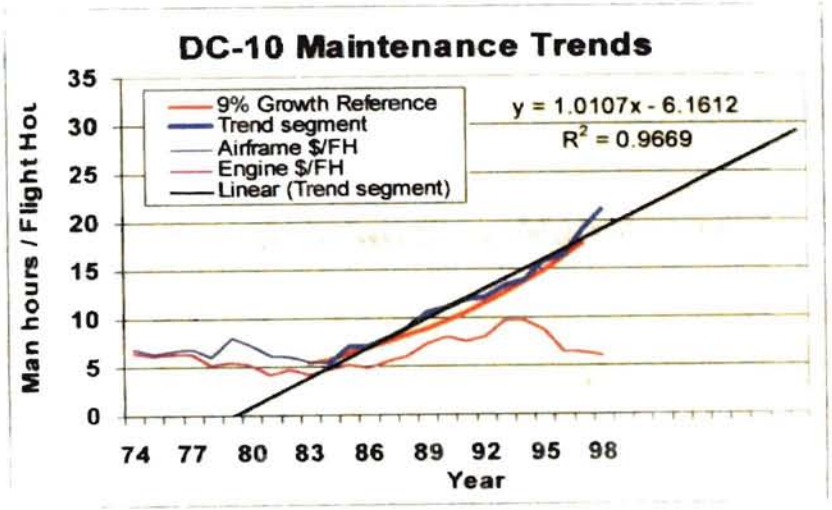


Figure 19. Fleet Wide Airframe Maintenance on DC-10.

Summary of the Findings

Airframe Labor

In summary, aging commercial airframe maintenance when measured in terms of man-hours per flying hour appear to be increasing. Aging fleet airframe maintenance appears to be increasing from a low of about 3.5% annually for the DC-9, to a high of 9% for the classic DC-10. The average fleet age included in this study also varied from approximately 20 years old for the classic 747 to approximately 28 years old for the classic Boeing 727.

The high coefficient of determination (R^2) for each measured target trend segment indicates a strong linear relationship between aircraft age and maintenance cost (Figure 20).

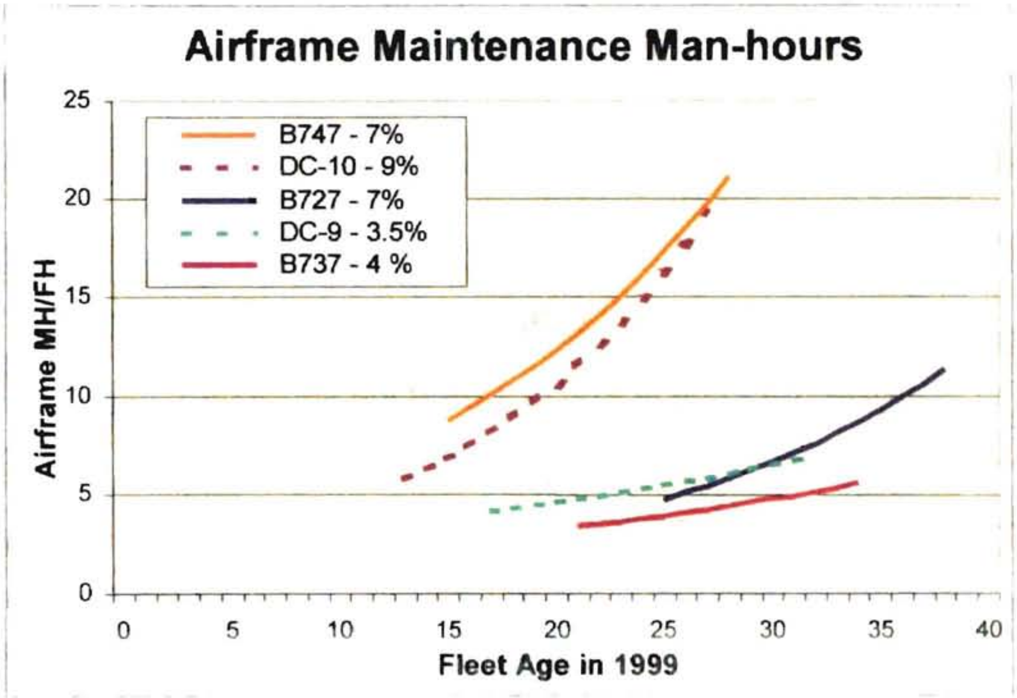


Figure 20. Annual Fleet Growth Rates Are Plotted as Function of Fleet Age.

Total Airframe Support Costs

Two samples of airframe costs were selected from the airframe database. One sample was taken from approximately 1985, and a second sample taken from 1998 or the last year the airline reported stable cost without any large fleet size adjustments. Table I presents the summative source data from the airframe growth analysis. For both 727-

100 and –200s there were 825 aircraft reporting costs in 1985, compared with a sample of only 704 aircraft reporting in 1998.

It is recognized that by not accounting for the variability of each aircraft, within each airline, may have the potential to understate the variability of the two data sets being compared. This risk was weighed and is considered acceptable due to the large fleet populations of each airline.

TABLE I

AIRFRAME MATERIAL COSTS PER FLYING HOUR

Type	1985	Qty.	1998	Qty
Alaska Air 727-100C	149.78	3	353.80	1
Alaska Air 727-200	82.83	19	685.22	11
American Air 727-100C	149.65	38	359.19	28
American Air 727-200	157.76	122	542.93	78
Continental Air 727-100C	166.26	15	408.08	7
Continental Air 727-200	160.54	93	349.46	83
Delta Air 727-200	111.93	143	199.91	153
Fed X 727-100C	87.31	12	972.58	62
Fed X 727-200	221.73	15	699.64	89
NW Air 727-100	154.74	9	256.45	9
NW Air 727-200	130.68	74	331.26	40
TWA 727-100	150.93	26	352.74	12
TWA 727-200	158.47	56	343.73	26
United Air 727-100	170.32	50	319.34	17
United Air 727-200	147.69	104	299.68	74
US Air 727-200	128.70	46	522.32	14
Total		825		704

Boeing 727 Airframe Cost Growth

The t-test confirmed that indeed these two samples were statistically different as confirmed by a calculated t-statistic of 5.728 and a t-Critical (two-tailed) value of 2.921 at a confidence level of .99 ($\propto = .01$) (Table II).

TABLE II

B727 AIRFRAME MATERIAL COST GROWTH T-TEST

	1985 Sample	1998 Sample
Mean	145.583	437.271
Variance	1100.018	40393.683
Observations	16.000	16.000
Hypothesized Mean Difference		0.000
df		16.000
t Stat		5.728
P (T.=t) one-tail		0.000
t Critical one-tail		2.583
P (T,=t) two-tail		0.000
t Critical two-tail		2.921

Given the real world limitations of available data, we accept the results of the t-test and conclude these two samples are statistically different beyond what could occur due to chance. For our purposes this test confirmed a difference between the 1985-airframe cost sample and the 1998 sample. This test was then repeated for each aging aircraft studied with the following results (Table III - X).

Boeing 737 Airframe Cost Growth

TABLE III

B737 AIRFRAME MATERIAL COSTS PER FLYING HOUR

Type	1985	Qty.	1998	Qty.
Alaska 737-200C	104.56	6	268	8
America West 737-200	62.54	29	132.86	18
American Air 737-200	157.83	20	326.80	9
Continental Air 737-200	120.00	68	244.83	13
Continental Air 737-	115.72	28	308.02	17
Delta 737-200	67	57	138.34	54
Southwest 737-200	77.72	35	214.85	42
United Air 737-300	217.83	50	317.84	59
US Airways 737-200	111.71	86	205.82	63
Total		825		704

The classic Boeing 737 – 100 and –200 t-test confirmed our suspicion that indeed these two samples were statistically different as confirmed by a calculated t-statistic value of 4.262 compared to a t-Critical (two-tailed) value of 2.977 at a confidence level of .99 ($\propto = .01$).

TABLE IV

B737 AIRFRAME MATERIAL COST GROWTH T-TEST

	1985 Sample	1998 Sample
Mean	114.99	23.971
Variance	2374.95	5330.14
Observations	9.00	9.00
Hypothesized Mean Difference		0.00
df		14.00
t Stat		4.262
P (T,=t) one-tail		3.945E-04
t Critical one-tail		2.624
P (T.=t) two-tail		7.889E-04
t Critical two-tail		2.9212.977

Boeing 747 Airframe Cost Growth

The classic Boeing 747 – 100 and –200 t-test confirmed our suspicion that indeed these two samples were statistically different as confirmed by a calculated t-statistic value of 5.42 compared to a t-Critical (two-tailed) value of 2.98 at a confidence level of .99 ($\propto = .01$).

TABLE V

B747 AIRFRAME MATERIAL COSTS PER FLYING HOUR

Type	1985	Qty.	1998	Qty.
Continental Air 747-100	230.28	2	489.00	2
Continental Air 747-200	265.68	5	498.48	7
Fed X 747-100	275.99	7	570.83	7
Fed X 747-200	132.21	2	533.00	9
Northwest Air 747-100	345.76	31	412.00	32
TWA 747-100	447.57	19	719.15	14
United Air 747-100	318.71	18	500.75	18
United Air 747-200	316.81	2	582.55	9
Total		86		98

TABLE VI

B747 AIRFRAME MATERIAL COST GROWTH T-TEST

	1985 Sample	1998 Sample
Mean	291.63	538.22
Variance	8387.32	8161.26
Observations	8.00	8.00
Hypothesized Mean Difference		0.00
df		14.00
t Stat		5.42
P (T.=t) one-tail		0.00
t Critical one-tail		2.62
P (T.=t) two-tail		0.00
t Critical two-tail		2.98

McDonnell Douglas DC-9 Airframe Cost Growth

The classic McDonnell Douglas DC-9 –10, -30 and -40 t-test confirmed our suspicion that indeed these two samples were statistically different as confirmed by a calculated t-statistic value of 3.578 compared to a t-Critical (two-tailed) value of 3.106 at a confidence level of .99 ($\propto = .01$).

TABLE VII

DC-9 AIRFRAME MATERIAL COSTS PER FLYING HOUR

Type	1985	Qty.	1998	Qty.
Continental DC9-10	117.37	11	245.48	7
Continental DC9-30	186.76	36	272.68	27
Delta DC9-30	116.90	36	356.69	36
Northwest DC9-10	141.13	33	196.23	19
Northwest DC9-30	184.15	60	325.26	113
Northwest DC9-40	93.42	11	173.71	12
TWA DC9-10	205.35	7	159.69	7
TWA DC9-30	142.02	36	497.49	33
TWA DC9-40	176.42	3	524.63	3
United Air DC9-10	179.87	75	281.75	72
Total		308		329

TABLE VIII

DC-9 AIRFRAME MATERIAL COST GROWTH T-TEST

	1985 Sample	1998 Sample
Mean	154.339	303.361
Variance	1387.454	15961.772
Observations	10.000	10.000
Hypothesized Mean Difference		0.000
df		11.000
t Stat		3.578
P (T,=t) one-tail		0.002
t Critical one-tail		2.718
P (T,=t) two-tail		0.004
t Critical two-tail		3.106

McDonnell Douglas DC-10 Airframe Cost Growth

The classic McDonnell Douglas DC-10–10 & -30 t-test confirmed our suspicion that indeed these two samples were statistically different as confirmed by a calculated t-statistic value of 4.32 compared to a t-Critical (two-tailed) value of 3.105 at a confidence level of .99 ($\propto = .01$).

TABLE IX

DC-10 AIRFRAME MATERIAL COSTS PER FLYING HOUR

Type	1985	Qty.	1998	Qty.
American Air DC 10-10	381.57	44	740.99	13
American Air DC 10-30	212.80	9	876.30	5
Continental Air DC 10-10	276.96	9	667.33	4
Continental Air DC 10-30	126.01	4	458.74	30
Fed X DC10-30	474.72	7	807.63	20
Northwest Air DC-10-30	158.81	5	333.53	15
United Air DC10-10	252.08	44	454.81	24
United Air DC 10-30	276.00	4	550.03	8
Total		126		119

TABLE X

DC-10 AIRFRAME MATERIAL COST GROWTH T-TEST

	1985 Sample	1998 Sample
Mean	269.86875	611.17
Variance	13018.82138	36771.86431
Observations	8	8
Hypothesized Mean Difference		0
df		11
t Stat		4.326222172
P (T,=t) one-tail		0.000601058
t Critical one-tail		2.718079486
P (T,=t) two-tail		0.001202117
t Critical two-tail		3.105815267

CHAPTER V

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

Introduction

The problem this study focused on was trying to improve aging aircraft cost forecasting methodology. Currently no recognized cost models account for cost growth as a function of aging. No industry recognized factors have been developed which accurately predict airframe maintenance cost growth as a function of time. The objective of this study was to quantitatively prove that airframe maintenance costs do indeed increase with age. The null hypothesis was therefore stated as "Airframe maintenance costs do not increase as an aircraft age."

Summary of Findings

This study reviewed 25 years of commercial airline maintenance cost records for the classic Boeing 727, 737, 747 and the classic McDonnell Douglas DC-9 and DC-10. This study performed a detailed year-by-year trend analysis of maintenance man-hours per flying hour and in each case documented very high coefficients of determinations with R^2 values that averaged over .80. Airframe maintenance when measured in terms of man-hours per flying hour are increasing between 3.5% annually for a DC-9 and 9.0% annually for the classic DC-10 aircraft. Airframe support costs are also increasing. Samples from

1985 and 1998 were compared for each classic heavy jet studied. Each sample showed a statistically significant increase as determined by a two-tailed t-test. Calculated t values were typically 3 to 5 times the t-critical value indicating statistically significant differences.

Conclusion

Aging aircraft cost models should account for airframe maintenance cost growth which increases between 3.5% and 9% annually for various heavy jet transport aircraft.

Recommendations

This study looked at aging aircraft costs on a very large scale. It did not control for individual aircraft tail numbers, individual maintenance practices nor the aircraft-basing environment. Results from this study should therefore be applied in a very general nature until additional research can be performed with greater controls in place. The study did not attempt to distinguish between fatigue, corrosion, nor stress corrosion damage. Use of these results should be considered based on equivalence of application. It is the recommendation of this study to apply airframe maintenance cost growth to all cost forecasting models involving classic heavy jet transport type aircraft. Annual airframe maintenance increases of a minimum of 3.5% annually may be anticipated in the general aging aircraft population. This general application should be applied when individual tail number specific trend analysis is not available. This value is representative of airframe maintenance growth documented for aircraft approaching 25 to 35 years of age. This study makes no prediction of cost growth outside the sample range, nor attempts to make application to aircraft constructed from non-aluminum structures.

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