

D O C U M E N T E D B R I E F I N G

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The Effects of Advanced Materials on Airframe Operating and Support Costs

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*Prepared for the
United States Air Force*

Project AIR FORCE

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PREFACE

Advanced materials—particularly polymer composites and titanium—are increasingly being used instead of aluminum in military airframe structures because of their superior strength and lighter weight. Understanding how these advanced materials may affect the operating and support costs of fielded military airframes is of critical importance to those making decisions on airframe acquisitions and related choice of materials.

This documented briefing focuses on the effects of advanced airframe materials on the operating and support costs of military aircraft. As such, it should be of interest to the cost analysis community, the military aircraft logistics community, and acquisition policy professionals in general.

The findings reported here are from research conducted as part of a larger project entitled “The Cost of Future Military Aircraft: Historical Cost-Estimating Relationships and Cost-Reduction Initiatives.” The principal goal of this project is to improve the tools available for estimating the cost of future weapon systems.

This study was conducted within the Resource Management Program of RAND's Project AIR FORCE and was sponsored by Lieutenant General Stephen B. Plummer, Principal Deputy Assistant Secretary of the Air Force (Acquisition). The technical points of contact were Jay Jordan, current technical director of the Air Force Cost Analysis Agency (AFCAA), and B. J. White-Olson, technical director of the AFCAA at the time of this study. The data used in this briefing were drawn from databases maintained by the Air Force Cost Analysis Agency, Air Force Materiel Command, Naval Center for Cost Analysis, and the Naval Aviation Logistics Data Analysis Group. Data presented in this briefing are current as of November 2001.

Other publications that report on the results of RAND's ongoing research in the area of military airframe cost-estimating include the following:

- *Aircraft Airframe Cost-Estimating Relationships: Study Approach and Conclusions* by R. W. Hess and H. P. Romanoff, R-3255-AF, 1987
- *Advanced Airframe Structural Materials: A Primer and Cost-Estimating Methodology* by Susan A. Resetar, J. Curt Rogers, and Ronald Wayne Hess, R-4016-AF, 1991
- *Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes* by Obaid Younossi, Michael Kennedy, and John C. Graser, MR-1370-AF, 2001
- *Military Airframe Acquisition Costs: The Effects of Lean Manufacturing* by Cynthia R. Cook and John C. Graser, MR-1325-AF, 2001
- *An Overview of Acquisition Reform Cost Savings Estimates* by Mark A. Lorell and John C. Graser, MR-1329-AF, 2001.

ABOUT PROJECT AIR FORCE

Project AIR FORCE, a division of RAND, is the U.S. Air Force federally funded research and development center for studies and analysis. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is performed within four programs: Aerospace Force Development; Manpower, Personnel, and Training; Resource Management; and Strategy and Doctrine.

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SUMMARY

Advanced materials—particularly polymer composites and titanium—are increasingly being used in the airframes of high-performance military aircraft. With that in mind, this study concentrates on answering a fundamental question: Do advanced airframe materials cost more to maintain than aluminum, which has historically been the most common material used in airframe structures?

Although considerable effort has been devoted to understanding the acquisition costs of advanced materials, very little is known about their operating and support (O&S) costs after an aircraft is fielded and fully operational.^{1, 2} In an effort to gain a better understanding of advanced-material O&S costs, we produced a methodology for forecasting those costs, which we present in this documented briefing.

APPROACH

To assess the effects of advanced materials on airframe O&S costs, we analyzed F/A-18 A/B/C/D part-level data³ and surveyed individuals in both the government and in industry.

Our approach for this study focuses on the development of material-weighting factors for the relative cost of maintaining airframe structural parts made of advanced materials. Maintenance data for aluminum parts served as the baseline. We estimated the material-weighting factors from historical base-level maintenance data for F/A-18 A/B/C/D airframe structural parts and from survey information provided by the Air Force's B-2 Program Office and by five major airframe contractors.

We restricted our study to airframe skins, access covers, and access doors because these airframe parts have proven to be those most susceptible to damage. We developed material-weighting factors for titanium parts and for composite parts with and without

¹ This study did not attempt to compare operating and support costs across services due to their inherent accounting differences.

² We did not address the impact of stealth technology on airframe costs because of the highly classified nature of the information on that technology. Thus, our report does not consider maintenance costs of stealthy aircraft, other than the basic costs of using various polymer composite parts without any stealth-related materials such as coatings.

³ Visibility and Management of Operating and Support Costs (VAMOSOC) and Equipment Condition Analysis (ECA) databases were used as data sources. The VAMOSOC database is maintained by the Naval Center for Cost Analysis (NCCA), and the ECA database is maintained by Naval Aviation Logistics Data Analysis (NALDA), a group supported by NAVAIR 3.0 Logistics. See Appendix C for further information on these databases.

aluminum honeycomb substructures,⁴ again using aluminum parts as the baseline. We then applied these cost weighting factors to quantify the relative difference in material properties, leading to a change in maintenance requirements and related costs, of titanium and composite parts compared with an all-aluminum airframe.

KEY FINDINGS

Senior-level decisionmakers in the Department of Defense should not be concerned about the use of advanced materials in military aircraft in terms of significant downstream operating and support costs. Structural materials drive only about 5 percent of the total O&S costs of maintaining airframes of military aircraft (these costs occur almost exclusively at the depot level). Thus, even if composites and titanium materials constitute a larger percentage of the airframe composition, the net change in total O&S costs should be negligible compared with the projected total O&S costs for a theoretical, all-aluminum fighter aircraft. This change does not take into account the benefits gained from the weight savings from those generally lighter-weight higher-strength materials. A key example is the cost savings resulting from reduction in fuel consumption due to decreased weight. In general, both composites and titanium are more expensive to repair than aluminum; however, titanium is more resistant to damage than either composites or aluminum.

How materials are used on an aircraft is far more important than their composition, as far as O&S costs go. Areas of an aircraft in which continual access by maintenance personnel is required have higher costs attached to them than those that require infrequent maintenance access. Thus, greater reliability of working parts in the airframe or avionics systems obviates the need for access to those parts, thus reducing maintenance costs regardless of material selection.

The following findings should be useful to cost analysts and aircraft designers who have responsibility for analyzing the costs of available choices for materials in airframes:

- The F/A-18 part-level analysis indicates that the amount of maintenance is a function of part type. Of the three types of parts we investigated, access doors are the most expensive to maintain.
- Results from the F/A-18 part-level analysis and from the B-2 Program Office survey indicate that composite materials require more maintenance than aluminum, with composite parts containing aluminum honeycomb substructures requiring the most maintenance. The results from our survey of airframe

⁴ Composite parts include sheet configurations, such as graphite epoxy sheets, and multilayered configurations with graphite epoxy sheets and aluminum honeycomb substructures. The sheet configuration has been used in airframe skins and some types of access covers, while the multilayered configuration has been used in access doors and certain other types of access covers. For this reason, we compared composite parts with aluminum honeycomb substructures (multilayered configuration) and without the substructures (sheet configuration).

contractors reinforce these conclusions about the maintenance requirements of composite materials.

- In the case of titanium, the F / A-18 and B-2 Program Office analyses were consistent in concluding that simple parts made of titanium sheets require less labor and cost less in consumable materials than those made of aluminum. However, results from the five major airframe contractors we surveyed indicate that superplastic-formed / diffusion-bonded (SPF / DB) and cast-titanium parts vary in their maintenance requirements as compared with aluminum, which suggests a link between material form and maintenance requirements.
- The material-weighting factors we developed depend strongly on part type. It seems clear that choosing the appropriate material type and form for the desired application—skins, access covers, or access doors—plays a crucial role in determining the maintenance costs for advanced materials compared with those for aluminum.

DIRECTIONS FOR FUTURE RESEARCH

Through this research we sought to estimate the differences in base-level maintenance costs related to the use of different airframe materials. We recognize that depot overhaul is the biggest cost driver, especially for cases in which corrosion-related costs are likely to be significant and composites would therefore become an attractive material for airframe structures.

Considering the limitations of existing databases, we believe that the only feasible way to obtain useful information for future research in this area is through questionnaires and follow-up interviews with military aircraft base and depot personnel. These experts would be able to provide an informed and accurate perspective on the total inspection, corrosion-prevention, and repair costs for airframe structural parts manufactured with advanced materials versus the costs for airframe parts manufactured with aluminum.

ACKNOWLEDGMENTS

We would like to thank the following government agencies and airframe contractors who provided us with valuable information for the research study: The Air Force organizations include the Air Force Cost Analysis Agency in Arlington, Virginia; the Air Force Materiel Command at Wright Patterson Air Force Base, Dayton, Ohio; and the Air Combat Command in Langley, Virginia. The Navy organizations include the NAVAIR 4.2 Cost Department at Patuxent River, Maryland; the Naval Center for Cost Analysis in Washington, D.C.; and the Naval Aviation Depot at North Island, San Diego. The program offices include the Joint Strike Fighter Program Office in Arlington, Virginia; the F-22 System Program Office at Wright Patterson Air Force Base; and the B-2 System Program Office at Tinker Air Force Base, Oklahoma City. The airframe contractors include Northrop Grumman, El Segundo, California; Lockheed Martin, Fort Worth, Texas, Marietta, Georgia, and Palmdale, California; and Boeing, Seattle and St. Louis.

We sincerely appreciate the assistance provided by the following individuals during the course of this project: Colonel David Gothard and Lieutenant Colonel John Kusnierek from the B-2 Program Office; Lawrence Stoll, John Johnston, and Cork Yager from the NAVAIR 4.2 Cost Department; Soumen Saha from Northrop Grumman, El Segundo; and Bryan Tom from Lockheed Martin, Ft. Worth.

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ACRONYMS AND ABBREVIATIONS

\$/FH/lb	Dollars per flying hour per pound
AFMC	Air Force Materiel Command
AFTOC	Air Force Total Ownership Cost
AVDLR	Aviation depot-level reparable
BMI	Bismaleimide
CAI	Composites Affordability Initiative
CAIG	Cost Analysis Improvement Group
CLS	Contractor logistics support
DB	Diffusion bonded
DBOF	Defense Business Operations Fund
DLR	Depot-level reparable
ECA	Equipment Condition Analysis
FH	Flying hour
FOD	Foreign object damage
FSD	Full-Scale Development
FY	Fiscal year
GFMGFS	Government-furnished materials and government-furnished services
ICS	Interim contractor support
JSF	Joint Strike Fighter
JSFPO	Joint Strike Fighter Program Office
lb	Pound
LMDSS	Logistics Management Decision Support System
LO	Low observable
MAJCOM	Major Command
MDS	Mission design series
MFHMA	Mean Flight Hours Between Maintenance Actions

MMH/FH	Maintenance man-hours per flying hour
MSD	Materiel Support Division
MTTR	Mean Time to Repair
MWF	Material-weighting factor
NALDA	Naval Aviation Logistics Data Analysis
NAVAIR	Naval Air Systems Command
NCCA	Naval Center for Cost Analysis
O&S	Operating and support
PCS	Permanent Change of Station
PDM	Programmed depot maintenance
POL	Petroleum, oil, and lubricants
PTWF	Part-type weighting factor
R&M	Reliability and maintainability
REMIS	Reliability and Maintainability Information System
SDLM	Standard Depot-Level Maintenance
SPF	Superplastic formed
TAD/TDY	Temporary additional duty / temporary duty
T/M/S	Type/model/series
VAMOSOC	Visibility and Management of Operating and Support Costs
WSCR	Weapon System Cost Retrieval System
WUC	Work unit code

BACKGROUND

Advanced materials—particularly polymer composites and titanium—are increasingly being used instead of aluminum in military airframe structures because of their superior strength and lighter weight. As a result, the Department of Defense is interested in understanding the effects of these advanced materials on the operating and support (O&S) costs of fielded military airframe structures.

Fielded aircraft are subjected to varying levels of mission-specific aerodynamic loads and are exposed to corrosive environments, and the effects from exposure to these conditions accumulate as an aircraft ages. Over time, structural damage is likely to occur. Typically, such damage is caused by fatigue¹ or corrosion, or interactions between the two. Although these problems are commonplace with metal parts, parts made from composites have no fatigue or corrosion-related issues.² However, they are susceptible to fiber breakage and ply delaminations caused by impact damage.

A recent study³ conducted for the Composites Affordability Initiative (CAI) program⁴ concluded that polymer composite parts with thin skins and aluminum honeycomb substructures^{5, 6} require more maintenance than any other type of polymer composite because of their susceptibility to impact damage and to corrosion resulting from water intrusion. Except for those parts with thin skins and aluminum honeycomb substructures, polymer composite parts were found to be robust and relatively free of impact damage, with no fatigue and corrosion problems. There were, however, several cases of damage resulting from engineering-design and operator errors.

¹ Fatigue-related structural damage results from repeated (constant or fluctuating) tensile and compressive stress.

² In a humid environment, metals such as aluminum are susceptible to galvanic corrosion when they are in contact with composites.

³ See Dubberly (2001). Dubberly examined the performance of airframe composite parts by visiting Department of Defense depots that support four U.S. military aircraft including the F-15, F-16, F/A-18 (excluding the F/A-18 E/F), and AV-8B.

⁴ CAI is a joint government-industry program with the objective of investigating technologies that reduce the life-cycle cost of military aircraft.

⁵ Composite parts include sheet configurations, such as graphite epoxy sheets, and multilayered configurations with graphite epoxy sheets and aluminum honeycomb substructures. The sheet configuration has been used in airframe skins and some types of access covers, while the multilayered configuration has been used in access doors and certain other types of access covers. For this reason, we compare composite parts with and without aluminum honeycomb substructures.

⁶ Aluminum honeycomb substructures were used primarily for their low manufacturing costs and weight savings as compared with the alternative of using built-up structures, which are more expensive and have associated weight penalties.

USING PART-LEVEL DATA TO ANALYZE COST DIFFERENCES

Taken together, engineering design and material composition determine how susceptible an airframe part is to damage. Analyses of engineering-design issues typically include variables such as part dimensions (length, width, thickness), shape (simple flat structures, complex structures with curvatures, very complex three-dimensional structures), weight, and joining mechanism (bolted or bonded), all of which contribute to meeting the load requirements in a particular location of the airframe. Material composition typically determines the mechanical properties of the material in a given part. Therefore, in determining O&S costs, analysts find it extremely difficult to isolate costs related to material composition from costs related to engineering-design issues.

One solution to the difficulty in isolating costs related to design versus costs related to material composition would be to compare the maintenance costs for parts that have similar design characteristics but are made of different materials. At a minimum, the comparison should include the weight of each part, grouped according to its functionality—e.g., airframe skins, access covers, or access doors—and grouped according to its material composition. Maintenance costs related to parts with similar functionality could then be classified by weight and material composition to provide information on the relative cost of using different materials.

RELATED RESEARCH ON AIRFRAME MAINTENANCE COSTS

Maintenance of airframe structural parts includes activities such as inspection, corrosion prevention, and repair procedures, which are documented during the initial fielding of an aircraft and periodically updated by knowledgeable experts experienced in the operation of a fully fielded aircraft. Repair of airframe structural parts encompasses all activities required to fix damaged parts, including any necessary inspections. Similar inspection requirements apply to repair of corrosion-related damage. In general, maintenance activities related to airframe structural parts fall into three categories: repair, corrosion prevention, and inspection.

Although a substantial amount of technical information exists on advances in inspection techniques, corrosion prevention, repair procedures, and in related support equipment, very little research has been conducted regarding maintenance-related costs for different airframe structural materials. The lack of research in this area is primarily due to the difficulty of obtaining part-level design data and related maintenance costs for airframe parts that are similar in design but whose materials differ. Past studies by NAVAIR (Johnson, 1994) and Cambridge Research Associates (1998) included part-level maintenance data at the base level (data collected at the base where the aircraft is fielded), but the data lacked information on part weight and therefore did not provide a basis for quantifying relative cost (i.e., because weight figures into the design of a part,

one cannot theoretically compare the maintenance costs of a 1-pound part with those for a 50-pound part).

The Air Force has conducted research on total maintenance cost attributable to weapon-system corrosion (NCI Information Systems, 1998). The Air Force study revealed that, in fiscal year (FY) 1996, 83.5 percent of the maintenance cost traced to weapon-system corrosion was incurred at the depots. The study took into account all inspection and maintenance activities related to corrosion, washing, sealant application and removal, and coating application and removal. The study indicated that corrosion-prevention activities—painting, washing, and inspection—were responsible for more than 20 percent of the total costs. This is an important finding because corrosion is specific to metals, and aluminum is the airframe material most susceptible to corrosion. The remaining 80 percent of the maintenance cost was attributable to repair, making repair a major cost driver. This was especially evident at the depots, where aircraft typically go through extremely thorough periodic overhauls known as programmed depot maintenance (PDM).⁷

In this study, we expanded upon previous research done on airframe maintenance related costs by analyzing and comparing the maintenance costs of airframe structural parts made of advanced materials with those made of aluminum. We present the results of that analysis in the following chapters.

⁷ The equivalent U.S. Navy term for PDM is Standard Depot-Level Maintenance (SDLM).

1. INTRODUCTION

Over Time, Military Airframes Are Weakened by Aerodynamic Loads and Corrosive Environments

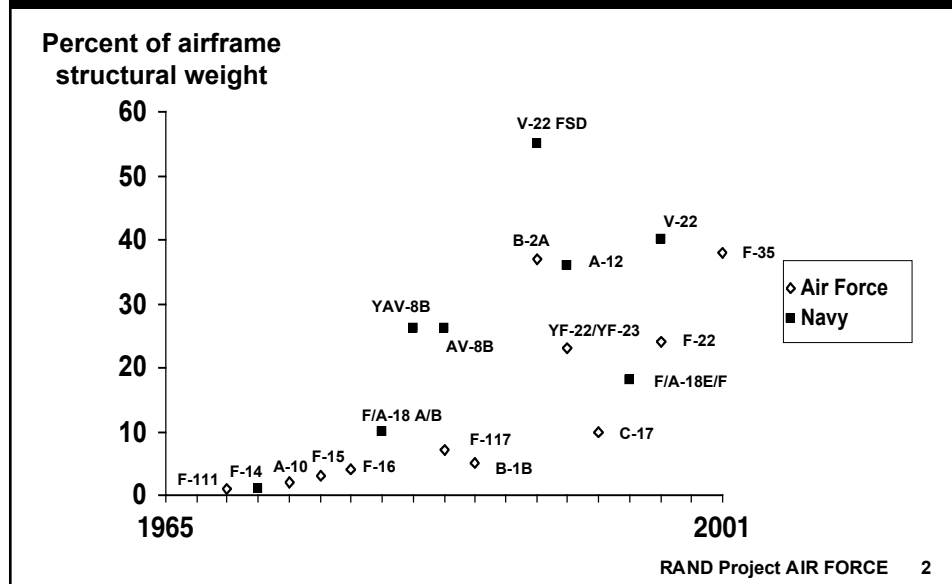
- **Structural damage is typically caused by fatigue, corrosion, and interactions between the two**
- **Aircraft parts made of composite materials appear to be attractive alternatives to metal parts**
 - **Have no fatigue and corrosion problems**
 - **But are susceptible to fiber breakage due to impact damage**

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Over time, the airframes of military aircraft are subjected to varying levels of mission-specific aerodynamic loads and to corrosive environments. The gradual weakening that results from the airframe's exposure to these conditions is enhanced by the aging process. The end result is structural damage, which is typically caused by fatigue or corrosion or interactions between the two.

While problems with fatigue and corrosion are commonplace with metal parts, composites are free from these problems. However, they are susceptible to fiber breakage and ply delaminations caused by impact damage.

Polymer Composite Content Is Increasing in All Types of Military Aircraft



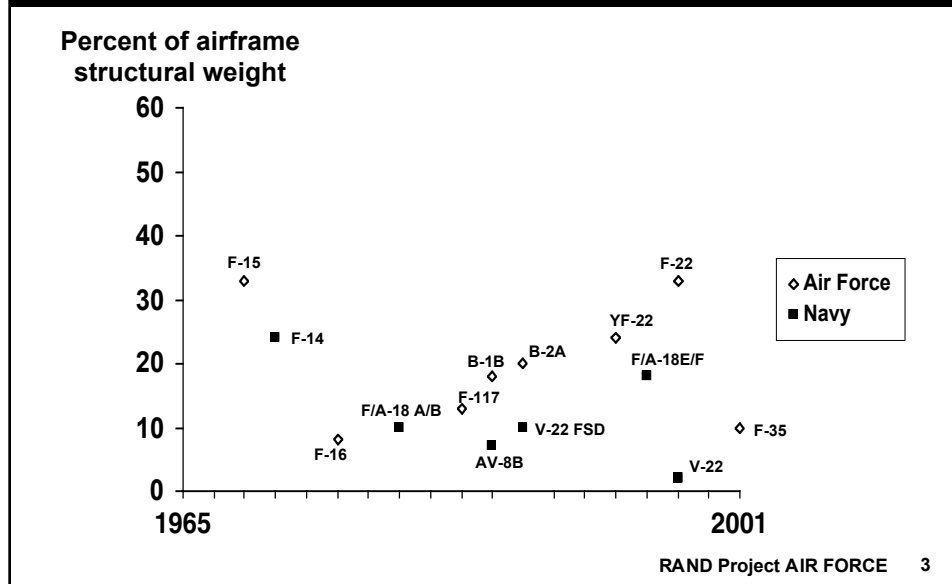
The percentage of structural weight that polymer composites contribute to military airframes has steadily increased over the years. In the 1960s and 1970s, composites constituted only a very small percentage of the structural weight of military airframes. Today, more than 20 percent of the airframe structural weight of modern fighter aircraft comes from composites. These composites have a higher strength-to-weight ratio than aluminum, which historically has been the metal most commonly used in the manufacture of military airframes.

The Navy's V-22 aircraft is an interesting case in which the initially high percentage of composites in the Full-Scale Development (FSD) version was later reduced significantly in the Engineering/Manufacturing Development and Production design by removing some of the composite materials and using metals instead. This change in materials reduced the weight of the aircraft and was expected to lower production costs. This is an example of using composite materials for their strength but not attempting to rely on them as a universal solution for airframe requirements.¹

The chart above highlights the growing need to understand the impact of composites on O&S costs as military aircraft structural design moves further away from conventional aluminum airframe structures.

¹ See Younossi, Kennedy, and Graser (2001) for a detailed discussion of composite design considerations.

Titanium Content in Dedicated Air Superiority Fighters Is High



As the chart above indicates, the use of titanium in military airframes shows no consistent trend over time. However, because of stringent temperature and other performance requirements, aircraft with a primary mission of air-to-air superiority (F-15, F-22) tend to have more titanium in their structures than do aircraft designed for other purposes, such as air-to-ground missions.

Study Objective: Determine Whether Advanced Materials Cost More to Maintain than Aluminum

- **Collect and analyze data for currently fielded aircraft in the Air Force, Navy, and Marine Corps**
- **Develop a methodology to forecast operating and support (O&S) costs of airframes that use advanced materials**

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This study concentrated on answering a fundamental question: Do advanced airframe materials cost more to maintain than aluminum?²

Although considerable effort has been spent on understanding the acquisition costs of materials, very little is known about their O&S costs after an aircraft is fielded and fully operational. This information is therefore crucial in making realistic life-cycle cost estimates for modern military aircraft.

The RAND study team established certain research objectives to evaluate the effects of advanced airframe materials on operating and support costs. First, we gathered data regarding the effects of advanced materials on the O&S costs of currently fielded systems in the U.S. Air Force, U.S. Navy, and U.S. Marine Corps, taking into account costs and activities at all levels of aircraft maintenance within these services. We then used the data to develop an improved cost-estimating methodology, discussed in the next subsection, for use by cost estimators and others who forecast O&S costs for military aircraft.³

² We did not address the impact of stealth technology on airframe costs because of the highly classified nature of the information on that technology. Thus, our report does not consider maintenance costs of stealthy aircraft, other than the basic costs of using various polymer composite parts without any stealth-related materials such as coatings.

³ This study did not attempt to compare O&S costs across services due to inherent differences in accounting practices across services.

Recent Milestone Estimates of O&S Costs for New Fighter Aircraft Accounted for Some Effects of Advanced Materials

- Milestone estimates were based on data collected for analogous platforms; methodologies applied one or more of three factors:
 - *Reliability and maintainability ratios*, which incorporate changes that result from material mix
 - *Material complexity factor*, which incorporates changes in material mix
 - *Flyaway cost ratio*, which incorporates flyaway cost changes, including those from material mix

New fighter (analogous platform)	R&M ratios	Material complexity factor	Flyaway cost ratio
JSF (F-18C)	Milestone II	N/A	Milestone II
F-22 (F-15C)	Milestones II & III	Milestone II	N/A
F/A-18E/F (F/A-18C)	Milestones II & III	N/A	N/A

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To see how cost estimators handled the issue of advanced airframe materials in recent Defense Acquisition Board milestone O&S estimates for major fighter programs, RAND examined the O&S estimates prepared by the Joint Strike Fighter Program Office (JSFPO) for the JSF, by the F-22 Program Office for the F-22, and by the Naval Center for Cost Analysis (NCCA) and Naval Air Systems Command (NAVAIR) Cost Department for the F/A-18 E/F. The examples shown in the chart above were chosen because they are the most recent fighter aircraft with significant percentages of advanced airframe materials in their airframe structures.

All estimates were based on O&S costs of analogous systems—i.e., gathering cost data on existing aircraft similar to the one for which costs are being estimated and adjusting the data for any differences. The JSF and F/A-18 E/F estimates were derived from the F/A-18C, while the F-22 estimate used the F-15 as an analog. In each case, the estimates employed one or more of the three factors listed in the chart above—the reliability and maintainability (R&M) ratio, the material complexity factor, and the flyaway cost ratio.

The R&M ratio compares the estimated system to its corresponding analogous platform. R&M metrics depend on a variety of factors besides material composition—for example, engineering design issues such as ply thickness for composites, mating of dissimilar materials, dimensional tolerances for parts required to withstand the required load specifications, and accessibility of parts requiring maintenance.

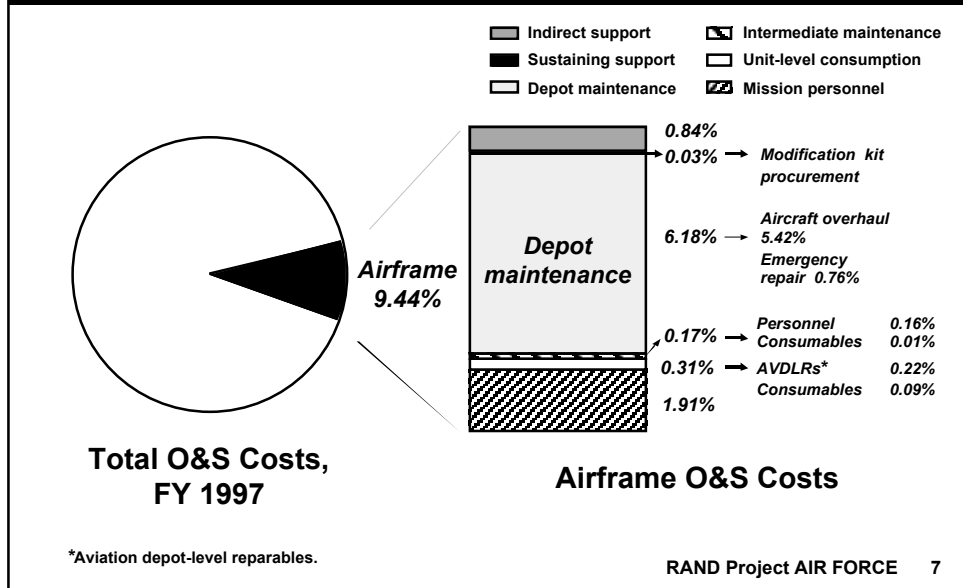
The F-22 Milestone II estimated by the F-22 Program Office uses a material complexity factor to explicitly account for the increased percentage of composites in the F-22 airframe as compared with the analogous F-15 C platform. For example, a complexity factor of 1.2 was based on the Program Office's engineering assessments for composites' manufacturing complexity. Although this factor increased the maintenance costs, it was more than offset by an improved R&M ratio, thereby reducing the overall estimated O&S costs related to the F-22 airframe when compared with the F-15 C.

The JSFPO used the flyaway cost ratio to incorporate cost-estimating changes owing to a change in the material mix based on the assumption that advanced material parts, which are inherently more expensive to manufacture than parts made of aluminum, will cost more to maintain than aluminum parts. The product of the flyaway cost ratio and the R&M ratio was used by the JSFPO to adjust the airframe-related O&S costs for the JSF in comparison with the analogous F / A-18 C platform.^{4, 5}

⁴ Because flyaway cost includes subsystems, avionics, and propulsion, it is an inaccurate metric to adjust for airframe O&S. The JSFPO realizes this problem and in the near future plans to use separate cost ratios for airframe, subsystems, avionics, and propulsion.

⁵ JSFPO used a separate cost factor to account for low-observable materials when compared with the non-stealthy F / A-18C as the analogous platform.

F/A-18 C Data Indicate That Depot Maintenance Is the Principal Cost Driver for Airframe O&S



To demonstrate the extent to which airframe maintenance costs contribute to total O&S costs, RAND obtained data on the total FY 1997 O&S costs of the F/A-18 C aircraft from the NAVAIR 4.2 Cost Department.^{6, 7} Nearly 10 percent of the total reported O&S costs are related to the airframe. These costs include military and civilian manpower, purchased services, and materials. In the illustration above, they are broken out into six major airframe-related categories.⁸

Focusing on airframe-related costs is appropriate because any differences in maintenance costs due to the use of advanced materials should show up in an examination of these areas.

As can be seen readily from the chart above, aircraft overhaul at the depot is the major cost driver for airframe-related O&S costs; the costs of depot maintenance are roughly three times larger than organizational and intermediate-level airframe-related costs.

⁶ The O&S costs shown here are in CAIG (Cost Analysis Improvement Group) format. See Appendix A for further information on the CAIG format, definitions of the categories, and an explanation of all elements contributing to the cost of airframe maintenance for each category.

⁷ The finding that depot maintenance is the principal cost driver for airframe maintenance does not change with multiple-year data.

⁸ There are no contractor-support costs related to airframe maintenance; therefore, this CAIG category is omitted from this illustration.

If one were to subdivide airframe-related depot costs into fixed and variable costs, the latter costs would be directly influenced by the choice of advanced materials. Although Navy databases do not provide this information, combining Air Force databases makes it possible to extract variable depot costs under a set of assumptions (see Appendix B for more information).

Our Initial Research Approach Required Detailed Maintenance Data from Bases and Depots

We planned to

- **collect maintenance cost data in three categories: corrosion prevention, inspection, and repair**
- **relate costs in each category to airframe part-level metrics (e.g., part weight and material composition) to compare maintenance costs of different materials**
- **exclude cost contributions from activities that are not related to materials (e.g., general inspection, aircraft washing, and painting)**

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Ideally, a study of this type would rely on actual cost data collected by airframe material type and part functionality,⁹ further classified into maintenance labor and consumable materials, and related support equipment costs in each relevant CAIG category (see Appendix A for more information on CAIG categories). In addition, weights of airframe parts within each material type and functionality would provide a means to classify the parts by weight and compare the maintenance data relative to aluminum as the baseline.

To acquire this kind of data, we needed to look at total maintenance costs of airframe structural parts for multiple Air Force, Navy, and Marine Corps platforms at the base and depot levels. We restricted our analysis to specific platforms with a high composite content and/or high titanium content, which could be compared against all-aluminum airframe structures. Our original intent was to collect data on the maintenance costs for each material type and functionality, including material-specific maintenance costs at the part level in the following three categories. However, we changed our approach because of certain problems and issues in these areas (discussed in the following subsections) that limited our data availability.

Corrosion Prevention: This category would have included all labor costs, consumable materials costs, and support equipment costs related to corrosion-

⁹ The term “functionality” refers to the specific function of the part. For example, access doors, access covers, and skins are each unique in their functions and are therefore categorized under a separate functionality category.

prevention activities but would have excluded aircraft washing and painting, which are considered to be universal requirements for all airframes, regardless of material differences.

Inspection: This category would have included all labor costs, consumable materials costs, and support equipment costs related to general inspection of the airframe structure (inspection of parts requiring repair was to be included in the repair category) but would have excluded visual inspection, which was considered to be a universal requirement for all airframes, regardless of material composition.

Repair: This category would have included all labor costs, consumable materials costs, and support equipment costs related to repair of airframe parts with a specific functionality and material composition. These repair activities would have included repair of damage caused by corrosion and operational stresses. In addition, the repair process costs would have included inspection costs specifically related to these repairs. We did not intend to further classify the repair actions according to the specific locations of the parts in the airframe because of the enormous amount of effort involved in collecting and analyzing this type of data.

Air Force and Navy Databases Did Not Have Material-Specific O&S Cost Data for Airframes

- **Depot overhaul costs did not provide details on corrosion prevention, inspection, and repair**
- **Base-level data also had deficiencies**
 - **Corrosion-prevention and general inspection costs were not collected at the part level**
 - **Information on weight and material composition of parts was not available**

RAND Project AIR FORCE 11

We examined several Air Force databases—e.g., the Air Force Total Ownership Cost (AFTOC), Reliability and Maintainability Information System (REMIS), and Weapon System Cost Retrieval System (WSCRS) databases, and the Navy Visibility and Management of Operating and Support Costs (VAMOS), Equipment Condition Analysis (ECA), and Logistics Management Decision Support System (LMDSS) databases. Unfortunately, none of them provided material-specific maintenance data. For example, the depot overhaul cost category, which had been previously identified as a major cost driver for airframe structures, did not provide material-specific details on corrosion-prevention, inspection, and repair costs. (A brief overview of the airframe-related data available in these databases is provided in Appendix C.)

During an aircraft overhaul, a significant amount of work is done on airframe parts. For purposes of this study, it was necessary to obtain costs related to airframe parts made of specific materials having a specific functionality. Because these data were not available in the databases, we needed to interview depot personnel who worked with selected platforms and use their experience and knowledge of airframe structural maintenance costs to fill in the gaps in the databases. This necessitated the development of a questionnaire. Although we were unable to use the questionnaire to interview depot-level personnel as intended (for reasons we note next), this avenue for data collection is one that should be revisited for future studies.

The base-level maintenance data available from the VAMOS, ECA, LMDSS, and REMIS databases were grouped under three main categories of activities: corrosion-prevention, inspection, and repair. In general, these three categories are similar in nature for both the Air Force and the Navy. Details on the limitations in the data follow:

Corrosion Prevention: All base-level corrosion-prevention activities are categorized under Work Unit Code (WUC) 02 for the Air Force and Work Unit Code 04 for the Navy. These activities pertain to all components and systems of the aircraft, namely, the airframe structure, subsystems, avionics, and propulsion. Generic corrosion-prevention costs related to aircraft washing and cleaning needed to be excluded from these costs. Besides the exclusion of these generic costs, corrosion-prevention activities that are specific to the airframe structure needed to be isolated, which, in turn, would have to be further subdivided to focus on material-specific corrosion-prevention costs at the part level. This subdividing would need to be done in an effort to compare the costs of all materials relative to aluminum as the baseline.

Inspection: All inspection activities are categorized under WUC 03 (Scheduled Inspections) and WUC 04 (Special Inspections) for the Air Force and WUC 03 (General Inspection) for the Navy. As is the case with corrosion-prevention activities, these costs include those related to airframe structures, subsystems, avionics, and propulsion, in addition to generic inspection activities, such as visual inspection, which were deemed to be independent of material composition. Besides excluding generic costs, inspection activities specific to the airframe structure needed to be isolated, which, in turn, would be further subdivided into material-specific inspection costs at the part level. Once again, this subdividing was to be done in an effort to compare the costs of all materials relative to aluminum as the baseline.

Unfortunately, because corrosion-prevention and inspection costs are not collected at the part level, it was difficult to conduct an analysis that would quantify differences in costs among airframe materials in order to compare them to costs for an aluminum baseline.

Repair: This category includes maintenance activities categorized under WUC 11 for the Air Force and the Navy. Part-level maintenance data were available at the five-digit WUC level for the Air Force platforms and seven-digit WUC level for the Navy platforms. Unfortunately, information on weight and material composition of the parts corresponding to the WUC was not available in the databases. This lack of information created the need to obtain part-level information from airframe contractors. We initially selected the AV-8B and F/A-18 A/B/C/D as the platforms to use to achieve a level of analysis this detailed. However, we were successful in obtaining pertinent data for only the F/A-18 platform from Boeing St. Louis.

We Modified Our Research Approach Due to Data Limitations

- **Developed questionnaires to get information from field maintenance experts at military bases and depots and from airframe contractors**
 - **B-2 Program Office responded as a test case**
 - **Northrop Grumman, Lockheed Martin, and Boeing provided useful data**
- **Collected part-level maintenance data for the F/A-18 platform**
- **Developed and applied material-weighting factors to account for the effect of advanced materials compared with aluminum as baseline**

RAND Project AIR FORCE 13

Because the available Air Force and Navy databases could not provide the material-specific airframe maintenance cost information we needed, we developed questionnaires to collect maintenance cost data from base and depot maintenance personnel who have insight into how actual costs should be allocated using their expert judgment in this area. The B-2 Program Office responded to our questionnaire as a test case.

We sent questionnaires to airframe contractors Northrop Grumman, Lockheed Martin, and Boeing. We also collected part-level airframe maintenance data at the base level¹⁰ for the F/A-18 platform.

Our research approach involved developing material-weighting factors (MWFs) for maintenance labor and consumable materials¹¹ and applying those factors to a hypothetical example. We used this approach to account for the effect of different airframe materials on maintenance costs as compared with aluminum as a baseline.

¹⁰ The bases include sea (aircraft carrier) and land bases supporting the platform.

¹¹ The materials include ones used in the repair process, such as nuts and bolts used for fastening; materials used in the welding process; resins used for bonding; paints used for corrosion protection; and other such raw materials.

Base and Depot Questionnaires Focused on Corrosion Prevention, Inspection, and Repair

We used this information to

- **help determine the percentage of total base and depot maintenance costs directly affected by airframe material differences**
- **develop relative weights for the maintenance of different materials**

RAND Project AIR FORCE 14

The questionnaires we developed for interviewing individuals at the bases and depots focus on the collection of material-specific maintenance cost data related to corrosion prevention, inspection, and repair of airframe structures. These questionnaires had the primary goal of (1) helping to determine the actual percentage of total base and depot maintenance costs directly affected by type of airframe material and (2) developing relative weights for the maintenance costs of different materials with respect to aluminum as the baseline, using actual cost data and the judgment of base and depot personnel who are experienced in this area. We sought responses to questions that addressed the following platforms:

- Air Force: C-17, A-10, F-15, F-16, F-117, B-1, and B-2
- Navy: F/A-18
- Marine Corps: AV-8B.

Logistics personnel at Air Force headquarters were reluctant to require MAJCOM (Major Command) personnel to fill out the questionnaire, particularly in light of the additional workload that had been created by the September 11, 2001, terrorist attacks. However, the B-2 Program Office responded with highly useful information because we visited them and asked them to fill out the questionnaire as a test case.

Navy bases and depots did not respond to the questionnaire, partly due to lack of personnel to support the activity and partly out of caution about providing their competitors with sensitive information about their depot costs.

2. B-2 PROGRAM OFFICE SURVEY

The B-2 Program Office Provided Material-Weighting Factors with Aluminum as Baseline

	Aluminum	Titanium	Composites without aluminum honeycomb	Composites with aluminum honeycomb
Labor hours to repair	1.0	1.5	2.0	2.2
Cost of consumables	1.0	1.8	2.0	3.0
Frequency of repair	1.0	0.3	0.6	0.6

- Effect of low-observable materials is not included
- Composites include graphite epoxy, graphite BMI (bismaleimide resin), and other advanced proprietary materials

RAND Project AIR FORCE 15

For purposes of this study, the B-2 Program Office provided us with material-weighting factors relative to aluminum as the baseline. The factors were based on the judgment of experts in this area.¹ Realizing that low-observable (LO) materials play a substantial role in maintenance costs for stealthy aircraft, the base-level personnel we interviewed were specifically asked to exclude the effect of LO materials on those costs. Stealthy airframes have additional costs related to coatings and other special treatments that must be removed before obtaining comparable maintenance costs relative to non-stealthy military airframe structures. (As noted in Part 1, for security reasons, we did not address the impact of stealth technology on airframe costs in this study.)

The table above shows that titanium and composites,² with and without aluminum honeycomb substructures, require more labor hours to repair and cost more in consumables than does aluminum, and composites with aluminum honeycomb substructures require more labor and consumables than composites

¹ Maintenance cost data from PDM was unavailable for the analysis because PDM was contracted out, and the contractor was reluctant to provide the requested information to the Program Office.

² Composites include graphite epoxy, graphite bismaleimide (BMI) resin, and other advanced proprietary materials.

without them. However, in terms of frequency of repair, all of these materials had better ratings than aluminum. This comparison suggested an approach that would use both the product of labor hours and frequency of repair and the product of the cost of consumables and frequency of repair as weighting factors in comparing titanium and composites against the aluminum baseline.

***Titanium Parts Require the Least Maintenance;
Composites with Aluminum Honeycomb
Substructures Require the Most***

Weighting factors for labor

Aluminum	Titanium	Composites w/o aluminum honeycomb	Composites with aluminum honeycomb
1.00	0.45	1.20	1.32

Weighting factors for consumables

Aluminum	Titanium	Composites w/o aluminum honeycomb	Composites with aluminum honeycomb
1.00	0.54	1.20	1.80

RAND Project AIR FORCE 16

As the table above shows, the weighting factors for both labor and consumables were lower for titanium than they were for aluminum, indicating that maintenance of titanium parts uses less labor and costs less in consumables than maintenance of aluminum parts. Composite parts with aluminum honeycomb substructures require a greater amount of maintenance labor and cost more in consumables than parts without the substructures, and both types of composites require more maintenance than aluminum.

3. AIRFRAME CONTRACTOR SURVEY

The Contractor Questionnaire Focused on Airframe Damage and Repair

- **Susceptibility to damage**
 - Assumed to be inversely related to mean flight hours between maintenance actions
- **Difficulty of repair**
 - Assumed to be directly related to mean time to repair
- **The product of the two terms above provides information on the total maintenance labor requirements of different materials compared with aluminum as the baseline**

RAND Project AIR FORCE 17

As part of this study, RAND sent questionnaires on airframe maintenance to several airframe contractors including Northrop Grumman in El Segundo, California; Boeing in Seattle, Washington, and St. Louis, Missouri; and Lockheed Martin in Ft. Worth, Texas, Marietta, Georgia, and Palmdale, California. The purpose of the questionnaires was to obtain weighting factors on various materials compared with aluminum as the baseline. The questions addressed three types of parts: simple, complex, and large unitized structures.

Simple parts were defined as those that are monolithic, minimally contoured, or flat. Examples of simple parts include covers, doors, fittings, flat skins, and panels. *Complex parts* were defined as those having contoured surfaces with curvatures or primary internal structures. Examples of complex parts include multicurvature skins, beams, inlet ducts, longerons, pylons, ribs, spars, and webs. *Large unitized structures* typically include parts such as bulkheads, frames, and keels.

We grouped material weighting factors under the following two categories:

Susceptibility to Damage: With an aluminum part as the baseline, a part made of a material other than aluminum and that has a greater susceptibility to damage than aluminum is rated at a value greater than 1.0. And the opposite is

true: A part made of a material other than aluminum that has a lower susceptibility to damage than aluminum is rated at a value less than 1.0.

This maintenance measure is assumed to be inversely related to Mean Flight Hours Between Maintenance Actions (MFHMA)¹ because a part with a higher MFHMA value requires less maintenance and, therefore, can be assumed to have a lower susceptibility to damage. Conversely, a part with a lower MFHMA value requires more maintenance and therefore is assumed to be more susceptible to damage.

Difficulty of Repair: With an aluminum part as the baseline, a part made of a material other than aluminum and that is more difficult to repair than aluminum was rated at a value greater than 1.0. Conversely, if the part is less difficult to repair than one made of aluminum, it is rated at a value less than 1.0. This maintenance category was assumed to be directly related to Mean Time to Repair (MTTR) because a part with a higher MTTR value requires more maintenance hours and, therefore, can be assumed to be more difficult to repair. Conversely, a part with a lower MTTR value requires fewer maintenance hours and can be assumed to be less difficult to repair.

The product of these two terms—susceptibility to damage and difficulty of repair—provides a weighting factor that would be comparable to the results on labor weighting factors obtained from the B-2 Program Office survey (see Part 2).

¹MFHMA includes scheduled and unscheduled maintenance actions. This inclusion is based on the assumption that a part that is more susceptible to damage will require more scheduled preventative maintenance and more unscheduled maintenance in the form of repair work.

Titanium Parts Are Less Susceptible to Damage than Aluminum Parts; Composites Are More Susceptible to Damage than Aluminum

Average input from all five contractor survey respondents

	Aluminum	Epoxy	BMI	Thermo-plastic	Titanium SPF/DB*	Titanium (cast)
Simple parts	1.0	1.5	1.5	1.3	0.9	0.8
Complex parts	1.0	1.5	1.5	1.3	0.9	0.8
Large unitized structures	1.0	1.5	1.5	1.3	0.9	0.8

NOTE: All composites include aluminum honeycomb substructures.

*SPF = superplastic formed
DB = diffusion bonded

RAND Project AIR FORCE 19

We received five responses to the questionnaire—one from Northrop Grumman, one from Boeing (responding as a single company), and three independent responses from the three Lockheed Martin sites. All responses were based on the judgment of experts in this area (see the table above).²

Average values of the weighting factors are shown for parts with simple shapes, parts with complex shapes, and large unitized structures.³ All composite categories—epoxy, BMI, and thermoplastic—include aluminum honeycomb substructures. However, the titanium parts rated in this survey have different materials properties than the titanium parts rated in the B-2 Program Office survey. In this case, the titanium parts are made by casting, superplastic forming, and diffusion bonding, in contrast to the simple sheet forms that were the subject of the B-2 Program Office survey.

² A number greater than one suggests that a part made of that material is more susceptible to damage than a part made of aluminum; a number less than one suggests the part is less susceptible to damage than one made of aluminum.

³ Parts with simple and complex shapes and large unitized structures made of aluminum all have a value of 1.0. Note that there is no relative weighting of simple aluminum parts over complex aluminum parts or over large unitized structures made of aluminum. It is conceivable that complex parts and large unitized structures may have a different susceptibility to damage based on their specific functionality and location in the airframe. For example, large unitized structures such as metal bulkheads that bear significant loads are not exposed to the external environment and, therefore, are less susceptible to corrosion and external damage.

Composite Parts Are More Difficult to Repair than Aluminum Parts; Titanium Parts Vary

Average input from all five contractor survey respondents

	Aluminum	Epoxy	BMI	Thermo-plastic	Titanium SPF/DB	Titanium (cast)
Simple parts	1.0	1.1	1.3	1.2	1.3	1.0*
Complex parts	1.0	1.1	1.1	1.1	1.4	1.0
Large unitized structures	1.0	1.2	1.4	1.2	1.6	1.0

NOTE: All composites include aluminum honeycomb substructures.

* Recommended value versus true average value

RAND Project AIR FORCE 20

Weighting factors on difficulty of repair that are based on the judgment of experts in this area⁴ were also provided by the airframe contractors (see the table above). Average values of the weighting factors are listed for parts with simple and complex shapes and for large unitized structures.^{5, 6} All composite categories—epoxy, BMI, thermoplastic—include aluminum honeycomb substructures.

⁴ A number greater than one suggests that a part made of that material is more difficult to repair than a part made of aluminum; a number less than one suggests the part is less difficult to repair than one made of aluminum.

⁵ Once again, simple and complex parts and large unitized structures made of aluminum are not weighted relative to one other. Therefore, the reader should use the weighting factors to compare a material's difficulty of repair with respect to aluminum only within a single part category, and not across parts categories.

⁶ In the case of simple cast titanium parts, the weighting factor obtained from one industry participant was unusually high. This data point overly influenced the resulting average weighting factor, creating a relatively higher value when compared with complex and large unitized parts made of titanium castings. We therefore suggest/recommend a value of 1.0 based on the other two part categories (complex and large unitized structures) having a value of 1.0.

Composites Require More Maintenance than Aluminum

	Aluminum	Epoxy	BMI	Thermo-plastic	Titanium SPF/DB	Titanium (cast)
Simple parts	1.00	1.65	1.95	1.56	1.17	0.80
Complex parts	1.00	1.65	1.65	1.43	1.26	0.80
Large unitized structures	1.00	1.80	2.10	1.56	1.44	0.80

NOTE: Labor weighting factor = susceptibility to damage x difficulty of repair.

RAND Project AIR FORCE 21

Labor-weighting factors for parts with simple and complex shapes and large unitized structures were derived from the product of the two average weighting factors: susceptibility to damage and difficulty of repair.

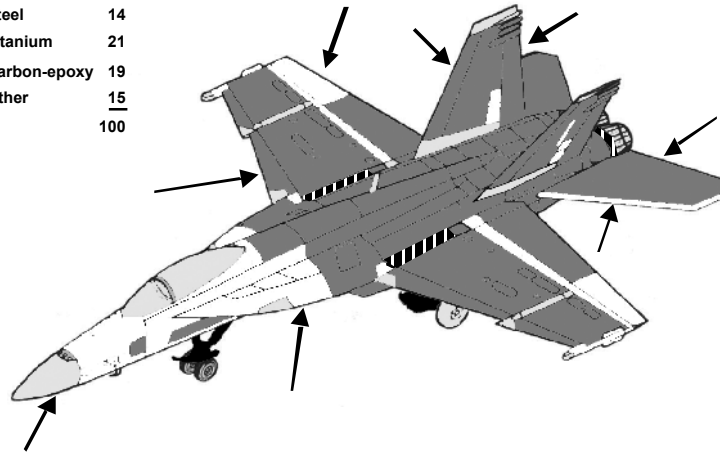
As shown in the table above, all composite materials are estimated to require more maintenance labor than aluminum. These trends are consistent with the results from the B-2 Program Office survey (see Part 2). However, titanium parts vary in this case because they are formed differently than the titanium parts used in the B-2 Program Office survey. This variation in the trends of weighting factors for differently formed titanium parts compared with aluminum is due to differences in the material properties of titanium parts made with different forming techniques.

4. F/A-18 PART-LEVEL ANALYSIS

Airframe Edges, Skins, Doors, and Panels Are the Parts Most Susceptible to Damage

Percent of structural weight

	Aluminum	31
	Steel	14
	Titanium	21
	Carbon-epoxy	19
	Other	15
		<u>100</u>



RAND Project AIR FORCE 22

In analyzing the effects of advanced materials on O&S costs, one must be cognizant of where most of the maintenance requirements arise. As illustrated in the drawing above of an F/A-18E/F, most maintenance is performed on the external surface or *wetted area*¹ of the airframe structure. This area of an airframe has the highest probability of damage due to a variety of reasons including human error, foreign object damage, environmental corrosion, and aerodynamic stress-induced fatigue.

The airframe components that are the most maintenance intensive include the edges, skins, doors, and panels, which are increasingly being made of advanced materials in modern fighter aircraft. The illustration above shows that a significant portion of the wetted area is made of composites (the darker shaded portions of the drawing).

¹ Wetted area is defined as the total surface area of a body that comes into contact with the fluid through which, or upon which, the body is moving. Thus, wetted area is equivalent to the exposed surface of the aircraft (Nayler, 1959).

Being Able to Estimate Maintenance Costs of These Parts Is Crucial

- **Access doors, covers, and skins account for about 15% of the airframe structural weight and a substantial portion of the wetted area on modern fighter aircraft**
- **Advanced materials are currently being used in all of these applications**

RAND Project AIR FORCE 23

In a typical modern fighter aircraft, about 15 percent of the weight of its airframe comes from access doors, covers, and skins. Advanced materials are used in all these applications. However, these parts account for most of the wetted area. Because these parts have a higher probability of being damaged, it is extremely important to be able to estimate the cost of maintaining those parts.

Although the B-2 Program Office and the airframe contractors we contacted for this study had supplied extensive information, we were unable to collect data that focused specifically on the three maintenance-intensive airframe components— access doors, covers, and skins. To fill that gap, we turned to actual maintenance data that was available for the F/ A-18 platform.

We Collected Extensive Maintenance Data for the F/A-18 A/B/C/D

- **Labor: maintenance man-hour data for calendar years 1985–2000**
 - 3,406,790 flight hours
 - Equipment Condition Analysis database
- **Consumables and aviation depot-level reparable for fiscal years 1995–1997**
 - 691,838 flight hours
 - Old VAMOSC database

RAND Project AIR FORCE 24

Using the Navy's ECA database, we collected 16 years' worth of maintenance-man-hour data derived from 3,406,790 flight hours for the F/A-18 A/B/C/D. Using the Navy's old VAMOSC database,² we also collected three years' worth of consumables and Aviation Depot-Level Repairable (AVDLR) data (for 1995 through 1997) derived from 691,838 flight hours.³

² This data was collected by the NAVAIR 4.2 Cost Department in 1999 prior to the recent restructuring of the database, which was done under the supervision of Naval Center for Cost Analysis (NCCA). The ECA database does not provide cost data on consumables and depot-level reparable. The Navy's Logistics Management Decision Support System is another data source but provides only two years' worth of cost information.

³ We recognize that using two different sources of data with two different time spans may not be the best approach to data collection. It is conceivable that the three-year part-level data for consumables and AVDLR from the VAMOSC database may have a different average value than the average value corresponding to 16 years' worth of maintenance data from the VAMOSC database. Unfortunately, during the time of this study, VAMOSC part-level data were unavailable due to the restructuring effort at the NCCA. As a result, we were limited to the three-year data available from NAVAIR. However, considering the large number of flight hours during this three-year period, we believe the data to be fairly representative at the parts level.

We Mapped and Categorized the F/A-18 Data

- **Analyzed 7-digit work-unit code part-level maintenance data**
- **Mapped 7-digit WUC to material characteristics using part-level information obtained from Boeing, St. Louis**
- **Categorized data on labor, consumable materials, and aviation depot-level reparables**
 - **Material type and form: aluminum sheets, titanium sheets, graphite epoxy sheets, and graphite epoxy sheets with aluminum honeycomb substructures**
 - **Part type: access doors, access covers, and skins**
 - **Weight range: 1–10 lbs**

RAND Project AIR FORCE 25

We mapped the seven-digit WUC part-level data to the corresponding material composition and part weight information obtained from Boeing, St. Louis. We classified data on labor, consumable materials, and AVDLR⁴ by material type and form and by part type in a weight range of one to ten pounds. This weight range had the largest number of aluminum, titanium, and composite parts that could be used to compare maintenance costs against each other. We took great care to ensure that the parts considered for the analysis did not contain any other materials. For example, skins containing a combination of aluminum sheets and graphite epoxy sheets or laminates were not included in the data set.

The material types and forms we considered were aluminum sheets, titanium sheets, graphite epoxy sheets or laminates, and graphite epoxy sheets with aluminum honeycomb substructures. We included access doors, access covers, and skins in our study because these types of parts constitute a major portion of the wetted area and are considered to be the most susceptible to damage.

⁴ The labor data was obtained as maintenance man-hours per flying hour (MMH/FH). Data for consumables and AVDLR were obtained in FY 2000 dollars.

Within Part Types, We Developed Material-Weighting Factors for Labor

Part type



1. Obtained maintenance-man-hours-per-flying-hour data for several parts within each part type
2. Categorized the part-level data by type of material
3. Computed the 16-year average of the MMH/FH data for each part within a given material
4. Computed the mean of the 16-year averages for all parts within a given material (averages of averages)
5. Divided the MMH/FH of each material by the corresponding value of aluminum sheet, which retained a baseline value of 1.00



Material-weighting factor

RAND Project AIR FORCE 26

To develop material-weighting factors for labor, we began with a part type (access door, access cover, or skin) and obtained maintenance man-hours per flying hour (MMH/FH) data for several parts within each part type. We classified the part-level data within the part type according to type of material: aluminum sheets, titanium sheets, graphite epoxy sheets or laminates, and graphite epoxy sheets with aluminum honeycomb substructures. We then computed the 16-year average⁵ of the MMH/FH data for each part within a given material type.

Next, we calculated the overall average of the 16-year average MMH/FH for all parts within a given material type. This calculation resulted in an average value of MMH/FH for each material type within a given part type.⁶ Finally, we divided the MMH/FH of each material type by the corresponding value of aluminum sheet. This calculation provided material weighting factors for labor

⁵ This procedure provides an average 16-year value and therefore does not take into account the impact of aging.

⁶ This procedure provides an average of part-level maintenance costs for all locations of the airframe and therefore does not take into account location-specific maintenance issues. Theoretically, parts on the lower portion of an aircraft probably receive more wear and tear and damage than parts on the upper portion of the same aircraft, but we found no practical means to account for these theoretical differences.

for all material types within a part type, which were numerically weighted relative to aluminum sheets as a baseline with a value of 1.00.

Similarly, We Developed Material-Weighting Factors for Consumables and AVDLRs

Part type



1. Obtained consumables data in FY 2000 dollars for several parts within each part type
2. Categorized the part-level data by type of material
3. Computed the 3-year average in FY 2000 dollars for each part within a given material
4. Divided the average values by corresponding part weights to get \$/FH/lb
4. Computed the mean of the 3-year averages for all parts within a given material to get \$/FY/lb for each material
5. Divided the \$/FH/lb of each material by the corresponding value of aluminum sheets



Material-weighting factor

RAND Project AIR FORCE 27

We followed a methodology similar to the one we used to develop material-weighting factors for labor to develop material-weighting factors for consumables and AVDLRs. Once again, we started with a part type and obtained consumables data in FY 2000 dollars for multiple parts within a part type. We classified the parts by type of material within the given part type. We calculated the three-year average of FY 2000 dollars/flying hour (FH) for each part of a particular material type within a given part type. We divided those average values by the corresponding part weights to get dollars per flying hour per pound (\$/FH/lb). This step was based on the assumption that the weight of the consumables used for maintenance should be proportional to the individual part weights.⁷

We then took the mean of the three-year average \$/FH/lb for all parts within a material type in a given part type to get a \$/FH/lb value for each material type. Finally, we divided this value for each material type within a part type by the value corresponding to aluminum sheets to get material weighting factors for all material types relative to aluminum sheets as a baseline with a value of 1.00.

⁷ We did not include this step with the labor data because we did not find any correlation between MMH/FH and part weights of a material type within a given part type.

We Also Developed Weighting Factors for Aluminum Access Doors, Access Covers, and Skins

Data for aluminum part types

- *MMH/FH for labor*
- *FY 2000 \$/FH/lb for consumables and AVDLRs*



Access covers
Skins



***Part-type weighting factors
for aluminum access
covers and doors with
aluminum skins as
baseline***

Access doors
Skins



RAND Project AIR FORCE 28

Using data for labor, consumables, and AVDLRs, we divided the values for aluminum access covers and doors by those for aluminum skins. This step produced weighting factors for doors and covers, with skins retaining a baseline value of 1.00.

Access Doors Are the Most Expensive Part to Maintain

Part-type weighting factors (PTWFs) for labor

Skins	1.00
Access covers	0.99
Access doors	1.20

PTWFs for consumables

Skins	1.00
Access covers	6.27
Access doors	12.01

PTWFs for consumables and AVDLRs

Skins	1.00
Access covers	6.27
Access doors	12.54

RAND Project AIR FORCE 29

The part-type weighting factors (PTWFs) for labor indicated that skins and access covers required almost the same amount of labor, while access doors required the most amount of labor of the three types of parts. A possible explanation for this finding may be that access doors are subjected to human handling with greater frequency than access covers and skins.

We calculated the PTWFs for consumables on the basis of the three years of maintenance data that were available. Again, access doors were the most expensive.

Including the cost of AVDLRs (excluding surcharges)⁸ resulted in a slight increase in the part-type weighting factor for aluminum access doors.

⁸ The Navy supply system applies a surcharge to parts that are provided to bases to replace damaged parts. We removed this surcharge to get the true costs.

***Titanium Parts Require the Least Labor to Maintain;
Graphite Epoxy Sheets with Aluminum Honeycomb
Substructures Require the Most***

Material-weighting factors for labor

Part type	Aluminum sheet	Titanium sheet	Graphite epoxy sheet	Graphite epoxy sheet with aluminum honeycomb
Skins	1.00	0.96	0.76	N/A
Access covers	1.00	0.30	1.38	2.04
Access doors	1.00	N/A	N/A	2.32

N/A = Not Available

RAND Project AIR FORCE 30

When considering MWFs within a part type, titanium skins and access covers require less maintenance than their aluminum counterparts, whereas access covers and access doors made of graphite epoxy sheets with aluminum honeycomb substructures require the most maintenance. Skins made of graphite epoxy sheets need less maintenance than those made of aluminum, whereas access covers made of graphite epoxy sheets require more maintenance than aluminum ones.

The high maintenance requirements for parts made of graphite epoxy sheets with aluminum honeycomb substructures are consistent with findings reported by Dubberly (2001). These maintenance requirements are driven by corrosion-related problems resulting from the intrusion of moisture in the honeycomb substructure and from impact damage on the thin graphite epoxy sheets or laminates.

Cost of Consumables Was Low for Titanium Parts and High for Composite Skins and Access Doors

Material-weighting factors for consumables

Part type	Aluminum sheet	Titanium sheet	Graphite epoxy sheet	Graphite epoxy sheet with aluminum honeycomb
Skins	1.00	0.65	1.81	N/A
Access covers	1.00	0.64	1.01	0.63
Access doors	1.00	N/A	N/A	1.38

N/A = Not Available

RAND Project AIR FORCE 31

When considering MWFs for consumables within a part type, titanium skins and access covers cost less than their aluminum counterparts, whereas skins with graphite epoxy sheets and access doors with graphite epoxy sheets with aluminum honeycomb substructures cost the most.

Including AVDLRs Increased the Weighting Factor for Only Graphite Epoxy Sheets with Aluminum Honeycomb Substructures

Material-weighting factors for consumables & AVDLRs

Part type	Aluminum sheet	Titanium sheet	Graphite epoxy sheet	Graphite epoxy sheet with aluminum honeycomb
Skins	1.00	0.65	1.81	N/A
Access covers	1.00	0.64	1.01	0.94
Access doors	1.00	N/A	N/A	1.45

N/A = Not Available

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In the table above, material-weighting factors for AVDLRs (excluding surcharges) have been included with the MWFs for consumables. For MWFs within a part type, only those parts made of graphite epoxy sheets with aluminum honeycomb substructures show an increased MWF, indicating that this type of material had the highest probability of failure⁹ likely to result in parts replacement.

⁹ When a damaged part cannot be repaired at the base, it is replaced by another part. At this point, the damaged part is considered to have been subjected to “failure.” The cost of replacing the “failed” part by another part corresponds to the cost attributed to AVDLR in the Navy or DLR (depot level repairable) in the Air Force. As a result, the cost of replacing these failed parts is directly proportional to their probability of failure.

5. ESTIMATING METHODOLOGY

The F/A-18 Analysis Became the Basis of Our Methodology for Estimating O&S Costs of Advanced Materials Used in Airframes

- We developed F/A-18 part-type and material-weighting factors based on actual data
- We assumed an all-aluminum airframe as the baseline and focused on parts of the external airframe that are most susceptible to damage (skins, covers, and doors)
- We designed five cases to assess how the cost of labor and consumables would be affected by part types made of advanced materials relative to an all-aluminum baseline
 - One case with all composites
 - Four cases using various combinations of materials

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We now turn to several notional examples¹ of how we used the data from the F/A-18 part-level analysis.

¹ Sizing effects are not considered when using the notional example of an all-aluminum airframe as a baseline. In reality, if one were to compare an all-aluminum airframe with an airframe made of titanium and/or composites, the former will be larger, heavier, and require a larger engine to accomplish the same mission.

**Using Values Derived from the F/A-18 Analysis,
We Calculated Total Weighting Factors for
Aluminum Airframe Parts**

Baseline case

Part type	Wt%*	Material	Labor (Wt%/100) x PTWF x MWF	Consumables (Wt%/100) x PTWF x MWF
Skins	40	Aluminum	$0.4 \times 1.00 \times 1.00 = 0.400$	$0.4 \times 1.00 \times 1.00 = 0.400$
Access covers	30	Aluminum	$0.3 \times 0.99 \times 1.00 = 0.297$	$0.3 \times 6.27 \times 1.00 = 1.881$
Access doors	30	Aluminum	$0.3 \times 1.20 \times 1.00 = 0.360$	$0.3 \times 12.01 \times 1.00 = 3.603$
Total weighting factor (aluminum baseline)			1.057	5.884

**Relative percentage of weight contributed by these three part types to the total weight of skins, access covers, and access doors*

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Once again considering skins, access covers, and access doors as the most maintenance-intensive parts of an airframe, we assumed a 40 percent/30 percent/30 percent split, respectively, by weight using a 100 percent baseline for these three part types. This breakout is representative of an airframe structure for a modern fighter aircraft.

The table above shows the baseline weighting factors for labor and consumables when parts are made entirely of aluminum. The weighting factor for each part type is the product of the weight fraction of the part, the part-type weighting factor, and the material-weighting factor. The total weighting factors for labor and consumables represent the sum of the individual factors for the three part types.

External Parts Made of Composites Are Substantially More Expensive to Maintain than Aluminum Parts

Case 1

Part type	Wt%	Material	Labor (Wt%/100) x PTWF x MWF	Consumables (Wt%/100) x PTWF x MWF
Skins	40	Graphite epoxy sheet	$0.4 \times 1.00 \times 0.76 = 0.304$	$0.4 \times 1.00 \times 1.81 = 0.724$
Access covers	30	Graphite epoxy sheet	$0.3 \times 0.99 \times 1.38 = 0.410$	$0.3 \times 6.27 \times 1.01 = 1.900$
Access doors	30	Graphite epoxy sheet with aluminum honeycomb	$0.3 \times 1.20 \times 2.32 = 0.835$	$0.3 \times 12.01 \times 1.38 = 4.972$
Total weighting factor (aluminum baseline)			1.549	7.596

Compared with all-aluminum baseline: 46.6% increase in labor

$$1.549 / 1.057 = 1.466$$

29.1% increase in consumables

$$7.596 / 5.884 = 1.291$$

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Next, we calculated the total weighting factors for labor and consumables for part types made of composite materials. In this case, we assumed the skins and access covers were made of graphite epoxy sheets or laminates, and the access doors were made of graphite epoxy sheets with aluminum honeycomb substructures.

We divided the total weighting factors for labor and consumables by the corresponding values previously obtained for aluminum parts. The result was a 46.6 percent increase in labor and 29.1 percent increase in consumables when skins, access covers, and access doors are made of composites.

We Considered Four Additional Combinations of Advanced Materials in External Airframe Parts

Cases 2—5

Skins	All graphite epoxy	All graphite epoxy	90% graphite epoxy, 10% titanium	All titanium
Access covers	All graphite epoxy	All graphite epoxy	25% graphite epoxy, 75% titanium	All titanium
Access doors	All graphite epoxy*	All aluminum	All titanium*	All titanium*

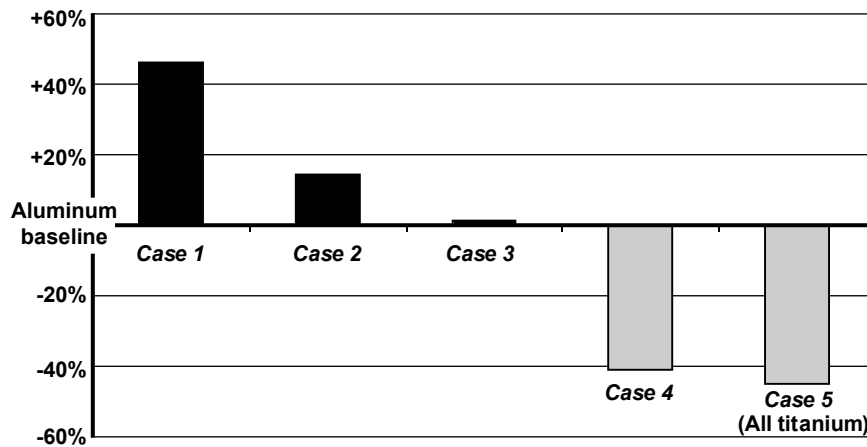
**Assumed to have the same material-weighting factor as that for access covers*

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Next, we developed four additional cases in which various combinations of advanced materials were used for the parts being considered. Here, Case 4 is representative of a modern airframe structure for a fighter aircraft.

As shown in the table above, access doors made of graphite epoxy sheets or titanium sheets were assumed to have the same material-weighting factor as their corresponding access covers.

Titanium Is the Most Attractive Option for Reducing Labor Costs



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Plotting the percentage change in labor for all the cases against an all-aluminum baseline shows the all-titanium case (Case 5) to be the most attractive option for reducing labor costs.

However, the labor costs for Case 4 are substantially lower than those for Cases 1 through 3, indicating that modern airframe structures could account for a significant decrease in maintenance labor when compared with an all-aluminum baseline for the three part types used in the estimation.

Titanium Parts Also Have the Greatest Effect on Reducing Cost of Consumables



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Similarly, plotting the percentage change in consumables for all five cases against an all-aluminum baseline reveals the all-titanium case (once again, Case 5) to be the most attractive one for reducing the cost of consumables.

As was also true for labor costs, Case 4 has significantly lower costs for consumables than the first three cases.

6. CONCLUSIONS

Key Conclusions

- Differences in airframe structural materials have a modest impact on total O&S costs
- Our F/A-18 analysis indicated maintenance to be a function of part type
 - Access doors are the most maintenance-intensive
- F/A-18 and B-2 survey data showed consistent trends for titanium and composites
 - Titanium is less maintenance intensive than aluminum
 - Composites are more maintenance intensive than aluminum
 - Composites with aluminum honeycomb substructures require the most maintenance
- Airframe contractor survey data for simple parts showed similar trends for composites; however, the trend was mixed for titanium because cast and SPF/DB parts were included
- Appropriate application of titanium and composites is key to reducing airframe-related operating and support costs

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Although differences in airframe structural materials appear to account for a small percentage of the total O&S costs of a typical military aircraft, the following generic conclusions should be useful to policymakers and cost analysts who are faced with addressing the issue of choice of airframe materials:

- The F/A-18 part-level analysis for base-level maintenance indicated that access doors are the most maintenance-intensive part.
- Results from the F/A-18 part analysis and the B-2 survey data indicated that parts made of composites require more maintenance than parts made of aluminum, with composite parts containing aluminum honeycomb substructures requiring the most maintenance. The level of maintenance required by composites was reinforced by the results from the airframe contractor survey, which led to the same conclusion.
- In the case of titanium, the F/A-18 and B-2 analyses were consistent in concluding that simple parts made of titanium sheets require less maintenance labor and have lower costs in consumables than aluminum. However, airframe contractor results indicated that simple superplastic-formed/diffusion-bonded (SPF/DB) and cast-titanium parts varied in their

maintenance requirements as compared with parts made of aluminum sheets, which suggests a link between material form and the intensity of maintenance.

- Material-weighting factors depend strongly on part type. That is, choosing the appropriate material type and form for the desired application—skins, access covers, or access doors—plays a crucial role in determining the maintenance costs of advanced materials as compared with aluminum.

7. FUTURE STUDY DIRECTIONS

Future Directions

- **Future research in this area will require collection of more-specific data**
- **Such data can be provided by base- and depot-level personnel through questionnaires and interviews**

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In this study, we sought to estimate the differences in base-level maintenance costs that are related to the use of different airframe materials. We recognize that depot overhaul is the biggest cost driver, especially where corrosion-related costs might be quite significant, thereby making composites an attractive material for airframe structures.

Considering the limitations of existing databases, we believe that the only feasible way to obtain useful information for future research in this area is through questionnaires and follow-up interviews with base and depot personnel. These experts would be able to provide an informed and accurate perspective on the total inspection, corrosion-prevention, and repair costs for parts made of advanced airframe structural materials versus the costs for aluminum parts.

APPENDIX A

AIRCRAFT OPERATING AND SUPPORT COST ELEMENT STRUCTURE

The Office of the Secretary of Defense Cost Analysis Improvement Group has established a single standard format for reporting aircraft O&S costs, which is presented in this appendix as an O&S cost-element structure. The following definitions for each category and subcategory of cost elements are from a CAIG document on estimating O&S costs (see Office of the Secretary of Defense, 1992).

1.0 MISSION PERSONNEL

- OPERATIONS
- MAINTENANCE
- OTHER MISSION PERSONNEL

2.0 UNIT-LEVEL CONSUMPTION

- 2.1 PETROLEUM, OIL, AND LUBRICANTS (POL)/ENERGY CONSUMPTION
- 2.2 CONSUMABLE MATERIAL/REPAIR PARTS
- 2.3 DEPOT-LEVEL REPARABLES
- 2.4 TRAINING MUNITIONS/EXPENDABLE STORES
- 2.5 OTHER

3.0 INTERMEDIATE MAINTENANCE (EXTERNAL TO UNIT)

- 3.1 MAINTENANCE
- 3.2 CONSUMABLE MATERIAL/REPAIR PARTS
- 3.3 OTHER

4.0 DEPOT MAINTENANCE

- 4.1 OVERHAUL/REWORK
- 4.2 OTHER

5.0 CONTRACTOR SUPPORT

- 5.1 INTERIM CONTRACTOR SUPPORT

- 5.2 CONTRACTOR LOGISTICS SUPPORT
- 5.3 OTHER

6.0 SUSTAINING SUPPORT

- 6.1 SUPPORT EQUIPMENT REPLACEMENT
- 6.2 MODIFICATION KIT PROCUREMENT INSTALLATION
- 6.3 OTHER RECURRING INVESTMENT
- 6.4 SUSTAINING ENGINEERING SUPPORT
- 6.5 SOFTWARE MAINTENANCE SUPPORT
- 6.6 SIMULATOR OPERATIONS
- 6.7 OTHER

7.0 INDIRECT SUPPORT

- 7.1 PERSONNEL SUPPORT
- 7.2 INSTALLATION SUPPORT

1.0 MISSION PERSONNEL

The mission personnel element includes the cost of pay and allowances of officer, enlisted, and civilian personnel required to operate, maintain, and support a discrete operational system or deployable unit. This includes the personnel necessary to meet combat readiness, unit training, and administrative requirements. For units that operate more than one type of aircraft system, personnel requirements will be allocated on a relative workload basis. The personnel costs will be based on manning levels and skill categories.

Note: Pay and allowances for officer and enlisted personnel should be based on the standard composite rate, which includes the following elements: basic pay, retired pay accrual, incentive pay, special pay, basic allowance for quarters, variable housing allowance, basic allowance for subsistence, hazardous duty pay, reenlistment bonuses, clothing allowances, overseas station allowances, uniform allowances, family separation allowances, separation payments, and Social Security contributions.

Pay and allowances for civilian personnel should be based on the standard composite rate, which includes the following elements: basic pay, additional variable payments for overtime, holiday pay, night differentials, cost-of-living allowances, and the government contribution to employee benefits, insurance, retirement, and the Federal Insurance Contribution Act.

1.1 OPERATIONS: The pay and allowances for the full complement of aircrew personnel required to operate a system. Aircrew composition includes the officers and enlisted personnel (pilot, nonpilot, and crew technicians) required to operate the aircraft of a deployable unit.

1.2 MAINTENANCE: The pay and allowances of military and civilian personnel who perform maintenance on and provide ordnance support to assigned aircraft, associated support equipment, and unit-level training devices. Depending on the maintenance concept and organizational structure, this element will include maintenance personnel at the organizational level and possibly the intermediate level. For example, in a typical deployable Air Force unit, intermediate-level maintenance personnel are normally assigned to the same wing as the organizational maintenance personnel. Depending upon the weapon system, the other Department of Defense components may integrate required intermediate-level maintenance personnel into a composite deployable unit according to the number of systems to be deployed. A brief description of these maintenance categories follows:

Organizational Maintenance. Personnel who perform on-equipment maintenance for unit aircraft.

Intermediate Maintenance. Personnel who perform off-equipment maintenance for unit aircraft. If intermediate-level maintenance is provided by a separate support organization (e.g., a centralized intermediate maintenance support activity) the costs should be reported in element 3.0, Intermediate Maintenance (External to Unit).

Ordnance Maintenance. Personnel performing maintenance and service functions for aircraft munitions, missiles, and related systems. Also includes personnel needed for loading, unloading, arming, and de-arming of unit munitions; inspecting, testing, and maintaining of aircraft weapons and release systems; activation and deactivation of aircraft gun systems; and maintenance and handling of the munitions stockpile authorized by the war reserve material plan.

Other Maintenance Personnel. Personnel not covered above. Includes those personnel that support equipment maintenance, simulator maintenance, and Chief of Maintenance functions related to the system whose costs are being estimated.

1.3 OTHER MISSION PERSONNEL: The pay and allowances of military and civilian personnel who perform unit staff, security, and other mission support activities. The number and type of personnel in this category will vary depending on the requirements of the particular system. These billets exist only to support the system whose costs are being estimated. Some examples are:

Unit Staff. Personnel required for unit command, administration, flying supervision, operations control, planning, scheduling, flight safety, aircrew quality control, and other such functions.

Security. Personnel required for system security. Duties may include entry control, close and distant boundary support, and security alert operations.

Other Support. Personnel required for staff information, logistics, ground safety, fuel and munitions handling, and simulator operations, and for special mission support functions such as intelligence, photo interpretation, and other such functions.

2.0 UNIT-LEVEL CONSUMPTION

Unit-level consumption includes the cost of fuel and energy resources; operations, maintenance, and support materials consumed at the unit level; stock fund reimbursements for depot-level reparable; operational munitions expended in training; transportation in support of deployed unit training; temporary additional duty / temporary duty (TAD / TDY) pay; and other unit-level consumption costs, such as purchased services for equipment leases and service contracts.

2.1 PETROLEUM, OIL, AND LUBRICANTS (POL)/ENERGY CONSUMPTION: The unit-level cost of POL, propulsion fuel, and fuel additives required for peacetime flight operations. Includes in-flight and ground consumption, and an allowance for POL distribution, storage, evaporation, and spillage. May also include field-generated electricity and commercial electricity if necessary to support the operation of the system.

2.2 CONSUMABLE MATERIAL/REPAIR PARTS: The costs of material consumed in the operation, maintenance, and support of an aircraft system and associated support equipment at the unit level. Depending on the maintenance concept or organizational structure, consumption at the intermediate level should be reported either in this element or in element 3.0, Intermediate Maintenance (External to Unit). Costs need not be identified at the level of detail shown here; the following descriptions are intended merely to illustrate the various types of materials encompassed in this element:

Maintenance Material. The cost of material expended during maintenance. Examples include consumables and repair parts such as transistors, capacitors, gaskets, fuses, and other bit-and-piece material.

Operational Material. The cost of nonmaintenance material consumed in operating a system and support equipment. Examples include coolants, deicing fluids, tires, filters, batteries, paper, diskettes, ribbons, charts, and maps.

Mission Support Supplies. The cost of supplies and equipment expended in support of mission personnel. Examples include items relating to administration, housekeeping, health, and safety.

2.3 DEPOT-LEVEL REPARABLES: The unit-level cost of reimbursing the stock fund for purchases of depot-level reparable spares (also referred to as exchangeables) used to replace initial stocks. DLRs may include repairable individual parts, assemblies, or subassemblies that are required on a recurring basis for the repair of major end items of equipment.

Note: Defense Management Report Decisions 901 and 904 of November 1989 proposed the establishment of a Defense Business Operations Fund (DBOF) under which DLRs would be consolidated under stock fund management. The cost of DLRs, previously a free issue to the consumer, must now be funded and budgeted by the resource user. A

surcharge is added to the price of DBOF items to recover the cost of stock fund operations.

2.4 TRAINING MUNITIONS/EXPENDABLE STORES: The cost of expendable stores consumed in unit-level training. Includes the cost of live and inert ammunition, bombs, rockets, training missiles, sonobuoys, and pyrotechnics expended in noncombat operations (such as firepower demonstrations) and training exercises.

2.5 OTHER: Included in this element are any significant unit-level consumption costs not otherwise accounted for. The costs identified must be related to the system whose operating and support requirements are being assessed. Possible examples are:

Purchased Services. The cost of special support equipment, communication circuits, and vehicles, including service contracts for custodial services, computers, and administrative equipment.

Transportation. The deployed unit transportation cost of moving primary mission and support equipment, repair parts, secondary items, POL, and ammunition to and from training areas. May also include transportation costs for items procured or shipped by the unit. Excluded are transportation costs for reparable acquired through DBOF.

TEMPORARY ADDITIONAL DUTY OR TEMPORARY DUTY PAY. TAD/TDY pay includes the cost of unit personnel travel for training, administrative, or other purposes, such as travel for crew rotations, deployments, or follow-on tests and evaluation. Includes commercial transportation charges, rental costs for passenger vehicles, mileage allowances, and subsistence expenses (e.g., per-diem allowances and incidental travel expenses).

3.0 INTERMEDIATE MAINTENANCE (EXTERNAL TO UNIT)

Intermediate maintenance performed external to a unit includes the cost of labor and materials and other costs expended by designated activities/units (third and fourth echelon) in support of an aircraft system and associated support equipment. Intermediate maintenance activities include calibration, repair, and replacement of parts, components, or assemblies, and technical assistance.

3.1 MAINTENANCE: The pay and allowances of military and civilian personnel who perform intermediate maintenance on an aircraft system, associated support equipment, and unit-level training devices.

3.2 CONSUMABLE MATERIAL/REPAIR PARTS: The costs of repair parts, assemblies, subassemblies, and material consumed in the maintenance and repair of aircraft, associated support equipment, and unit-level training devices.

3.3 OTHER: Included in this element are any significant intermediate maintenance costs not otherwise accounted for. For example, this element could include the cost of transporting subsystems or major end items to a base or depot facility.

4.0 DEPOT MAINTENANCE

Depot maintenance includes the cost of labor, material, and overhead incurred in performing major overhauls or maintenance on aircraft, their components, and associated support equipment at centralized repair depots, contractor repair facilities, or on site by depot teams. Some depot maintenance activities occur at intervals ranging from several months to several years. As a result, the most useful method of portraying these costs is on an annual basis (e.g., cost per aircraft system per year) or on an operating-hour basis.

Note: The cost of DLRs, or exchangeables, acquired through DBOF should be reported in element 2.0, Unit-Level Consumption.

4.1 OVERHAUL/REWORK: This element includes labor, material, and overhead costs for overhaul or rework of aircraft returned to a centralized depot facility. Includes programmed depot maintenance, analytic condition inspections, and unscheduled depot maintenance. Costs of major aircraft subsystems (i.e., airframe, engine, avionics, armament, support equipment) that have different overhaul cycles should be identified separately within this element.

4.2 OTHER: Included in this element are any significant depot maintenance activities not otherwise accounted for. For example, this element could include component repair costs for reparable items not managed by the DBOF, second-destination transportation costs for weapons systems or subsystems requiring major overhaul or rework, or contracted unit-level support.

Note: Not all reparable items are acquired through DBOF. Centrally funded accounts may continue to finance items such as classified program DLRs, conventional and nuclear munitions items, and certain cryptologic electronics and telecommunication items.

5.0 CONTRACTOR SUPPORT

Contractor support includes the cost of contractor labor, materials, and overhead incurred in providing all or part of the logistics support required by an aircraft system, subsystem, or associated support equipment. Contract maintenance is performed by commercial organizations using contractor personnel, material, equipment, and facilities or government-furnished material, equipment, and facilities. Contractor support may be dedicated to one or multiple levels of maintenance and may take the form of interim contractor support (ICS) if the services are provided on a temporary basis or contractor logistics support (CLS) if the support extends over the operational life of a system. Other contractor support may be purchased for engineering and technical services.

5.1 INTERIM CONTRACTOR SUPPORT: ICS includes the burdened cost of contract labor, material, and assets used in providing temporary logistics support to a weapon system, subsystem, and associated support equipment. The purpose of ICS is to provide total or partial logistics support until a government maintenance capability is developed.

5.2 CONTRACTOR LOGISTICS SUPPORT: CLS includes the burdened cost of contract labor, material, and assets used in providing support to an aircraft system, subsystem, and associated support equipment. CLS funding covers depot maintenance and, as negotiated with the operating command, necessary organizational and intermediate maintenance activities. If CLS is selected as the primary means of support, all functional areas included in the CLS cost should be identified.

5.3 OTHER: Included in this element are any contractor support costs not otherwise accounted for. For example, if significant, the burdened cost of contract labor for contractor engineering and technical services should be reported under this subcategory.

Note: Contractor support during the pre-operational phase of a system is typically funded as a system development or investment cost. However, post-operational contractor support is an O&S cost and should be addressed in this element.

After the ICS period, the government assumes responsibility for supporting a weapon system. However, contractor support may still be employed in specific functional areas, such as sustaining engineering, software maintenance, simulator operations, and selected depot maintenance functions. Applicable contractor costs should be reported against these elements in the Cost Element Structure (CES). To avoid double-counting, the contractor support element should be annotated to identify any contractor costs that are reported in other elements.

6.0 SUSTAINING SUPPORT

Sustaining support includes the cost of replacement support equipment, modification kits, sustaining engineering, software maintenance support, and simulator operations provided for an aircraft system. War readiness material is specifically excluded.

6.1 SUPPORT EQUIPMENT REPLACEMENT: This element includes the costs incurred to replace equipment that is needed to operate or support an aircraft, aircraft subsystems, training systems, and other associated support equipment. The support equipment being replaced (e.g., tools and test sets) may be unique to the aircraft or it may be common to a number of aircraft systems, in which case, the costs must be allocated among the respective systems.

Note: This element addresses replacement equipment only. The costs of initial support equipment are specifically excluded.

6.2 MODIFICATION KIT PROCUREMENT/INSTALLATION: This element includes the costs of procuring and installing modification kits and modification kit initial spares (after production and deployment) required for an aircraft and associated support and training equipment. It includes only those modification kits needed to achieve acceptable safety levels, overcome mission capability deficiencies, improve reliability, or reduce maintenance costs. It excludes modifications undertaken to provide additional operational capability not called for in the original design or performance specifications.

6.3 OTHER RECURRING INVESTMENT: Included in this element are any significant recurring investment costs not otherwise accounted for.

6.4 SUSTAINING ENGINEERING SUPPORT: This element includes the labor, material, and overhead costs incurred in providing continued systems engineering and program management oversight to determine the integrity of a system, to maintain operational reliability, to approve design changes, and to ensure system conformance with established specifications and standards. Costs in this category may include (but are not limited to) government and/or contract engineering services, technical advice, and training for component or system installation, operation, maintenance, and support.

6.5 SOFTWARE MAINTENANCE SUPPORT: This element includes the labor, material, and overhead costs incurred after deployment by depot-level maintenance activities, government software centers, laboratories, or contractors for supporting the update, maintenance and modification, integration, and configuration management of software. It includes operational, maintenance, and diagnostic software programs for the primary system, support equipment, and training equipment. The respective costs of operating and maintaining the associated computer and peripheral equipment in the software maintenance activity should also be included. Not included are the costs of major redesigns, new development of large interfacing software, and modifications that change functionality.

6.6 SIMULATOR OPERATIONS. This element includes the costs incurred to provide, operate, and maintain on-site or centralized simulator training devices for an aircraft system, subsystem, or related equipment. This element may include the labor, material, and overhead costs of simulator operations by military and/or civilian personnel, or by private contractors.

Note: On-site simulator operations and maintenance that are an integral part of unit manning and unit consumption should be reported as unit-level mission costs for the system in question. However, the costs of all contract-funded simulator operations and all centralized government simulator operations should be reported in this element.

6.7 OTHER: Included in this element are any significant sustaining support costs not otherwise accounted for. Examples might include the costs of follow-on operational tests and evaluation, such as range costs, test support, data reduction, and test reporting.

7.0 INDIRECT SUPPORT

Indirect support includes the costs of personnel support for specialty training, permanent changes of station, and medical care. Indirect support also includes the costs of relevant host installation services, such as base operating support and real property maintenance.

7.1 PERSONNEL SUPPORT: Personnel support includes the cost of system-specific and related specialty training for military personnel who are replacing individuals lost through attrition. Also included in this element are permanent change of station costs

and the cost of medical care. Each of these elements should be addressed separately. Descriptions of the elements follow:

Specialty Training. This element includes the cost of system-specific training (noninvestment funded) and specialty training for military personnel who are replacing individuals lost through attrition. For example, specialty training costs may include undergraduate pilot training, nonpilot aircrew training, nonaircrew officer training, and enlisted specialty training. Replacement specialty training costs should be calculated for those personnel associated with the system being investigated. Training costs should include government non-pay-related training costs (course support costs, materials, per diem, travel, and such) as well as the cost of pay and allowances for trainees, instructors, and training support personnel. Excluded are recruiting, accession, basic military training, and separation costs.

Note: The cost of initial course development and training of service instructors at contractor facilities is normally categorized as a system investment cost. However, the follow-on training costs of military and civilian personnel attending factory schools, as well as the cost of attending service-conducted schoolhouse specialty training, are O&S costs and should be reported in this element.

Normally, the costs of acquisition for recruiting, accession, and basic military training will not be included. However, if a significant change in service recruiting and training objectives is required in order to support the system being assessed, then these costs should be addressed.

Permanent Change of Station (PCS). This element includes the cost of moving replacement personnel to and from overseas theaters and within the continental United States.

Medical Support. This element includes the cost of personnel pay and allowances and material needed to provide medical support to system-specific mission and related military support personnel.

7.2. INSTALLATION SUPPORT: This element consists of personnel who are normally assigned to the host installation and are required for the unit to perform its mission in peacetime. It includes only those personnel and costs that are directly affected by a change in the number of aircraft and associated mission personnel. Functions performed by installation support personnel include the following:

Base Operating Support. The cost of personnel pay and allowances and material necessary to provide support to system-specific mission-related personnel. Base operating support activities may include functions such as communications, supply operations, personnel services, installation security, base transportation, and other such functions.

Real Property Maintenance. The cost of personnel pay and allowances, material, and utilities needed for the maintenance and operation of system-specific mission-related real property and for civil engineering support and services.

CAIG COST ELEMENTS AFFECTED BY THE AIRFRAME

1.0 Mission Personnel

Maintenance personnel having airframe maintenance duties

2.0 Unit Level Consumption

Depot-Level Reparables
Consumable materials

3.0 Intermediate Maintenance

Maintenance personnel having airframe maintenance duties
Consumable materials

4.0 Depot Maintenance

Aircraft overhaul
Emergency repair

5.0 Contractor Support

Airframe-related contractor logistic support at the base and the depot

6.0 Sustaining Support

Modification kit procurement and support equipment replacement related to airframe maintenance

7.0 Indirect Support

Training related to airframe maintenance.

All CAIG elements related to airframe maintenance are shown in the previous list, with examples of the types of costs under each of the seven operating and support cost categories. Base-level/organizational-level costs include salaries of organizational or on-equipment maintenance personnel (categorized under Mission Personnel) and intermediate or off-equipment maintenance personnel (categorized under Intermediate Maintenance), cost to remove and replace airframe components (categorized under Unit Level Consumption as AVDLRs for the Navy and DLRs for the Air Force), cost of consumable materials used for organizational or on-equipment maintenance (categorized under Unit-Level Consumption as consumable material costs), and intermediate or off-equipment maintenance (categorized under Intermediate Maintenance). Any contractor logistic support at the base may be identified separately under the respective section(s) or categorized under Contractor Support.

Airframe-related maintenance costs at the depot are categorized under Depot Maintenance, which includes aircraft overhaul and emergency repair costs. The CAIG reporting format does not provide a further breakout of these depot costs into airframe, avionics, and subsystems components. Any contractor logistic support at the depot may be identified separately under this section or categorized under Contractor Support.

Costs of modification kit procurement and replaced support equipment for airframe maintenance at the base and depot levels are reported under Sustaining Support as listed earlier. Finally, personnel training costs for airframe maintenance are listed under Indirect Support.

APPENDIX B

AIRFRAME MATERIAL-SPECIFIC MAINTENANCE COSTS IN DEPOT OVERHAUL

Due to the difficulty in obtaining material-specific airframe maintenance data from the existing databases on airframe O&S costs, we attempted to scope the airframe maintenance costs related to depot overhaul, which was identified as the major airframe-related cost. To assess the impact of various airframe materials on depot overhaul costs, we separated the direct labor and consumable materials portion of these costs from the fixed costs (overhead, general and administrative expenses, and other such costs) because only the direct categories would be affected by differences in materials. The fixed costs and other portions of the depot costs should not be affected by differences in airframe materials, given that they represent costs such as overhead and those related to depot personnel travel expenses. While this division into fixed and variable cost components was not possible using the Navy databases, it was feasible for the Air Force platforms by using a combination of two different data sources: AFTOC database and the WSCRS database.

We started with the depot overhaul costs in Section 4.0 of the AFTOC CAIG format data for FY 1998–FY 2000. For each of the listed platforms, we collected depot overhaul data for only engines in the same fiscal years and subtracted the depot overhaul costs for engines from the corresponding total depot overhaul costs. The resulting cost was assumed to contain aircraft overhaul costs and Materiel Support Division–exempt (MSD-exempt)¹ off-equipment maintenance costs for airframe, avionics, and subsystems.

FY 1998–FY 2000 WSCRS data were used to obtain the fraction of costs applicable to aircraft overhaul and MSD-exempt airframe off-equipment maintenance. This fraction was then applied to the AFTOC depot overhaul costs (excluding engine overhaul costs)² to exclude the avionics and subsystems off-equipment costs. The residual costs, which we felt represented the airframe-only costs, were about 70 percent of the non-engine-

¹ The MSD is part of the Supply Management Activity Group and is a division of the Defense Working Capital Fund. Repaired aircraft components are stocked as inventory in this division. Air Force bases purchase DLR items from this division, which includes a surcharge in the price paid. An MSD-exempt item refers to aircraft components not obtained from the MSD supply system. In this context, it refers to off-equipment repair of aircraft components at the depot where the overhaul is performed.

² Recognizing the fact that the AFTOC database lists obligations and the WSCRS database lists expenditures, this exercise assumes that the percentage allocation toward airframe off-equipment maintenance and aircraft overhaul at the depot level is the same in both. This assumption was necessary to isolate the cost contributions toward maintenance labor and consumable materials related to the airframe.

related depot overhaul costs. WSCRS data were used to subdivide the airframe costs into fixed-investment costs and variable costs, which include organic labor, consumable materials, contractor costs, and government-furnished materials and government-furnished services (GFMGFS). The last two categories (contractor costs and GFMGFS) include labor and consumable materials and were not identified separately in the WSCRS database. The overall average of the three fiscal years' (FY 1998–FY 2000) worth of data for the A-10 A, F-15 A, F-15 B, F-15 C, F-15 D, F-15 E, F-16 A, F-16 B, F-16 C, and F-16 D show the variable costs amount to only 42 percent of depot overhaul costs excluding engines, as shown in Figure B-1.³

Implementing this methodology, the variable depot costs are expressed as a percentage of total O&S costs using AFTOC CAIG format data, which provide the total operating and support costs for a given platform. Using an average of three fiscal years (FY 1998–FY 2000), Figure B-2 shows that the depot variable costs (the ones most likely to be affected by airframe material differences) are a small fraction of the total O&S costs for the ten platforms shown; that the depot variable costs range from a high of about 4.5 percent to a low of less than one-half of one percent of the total O&S costs.

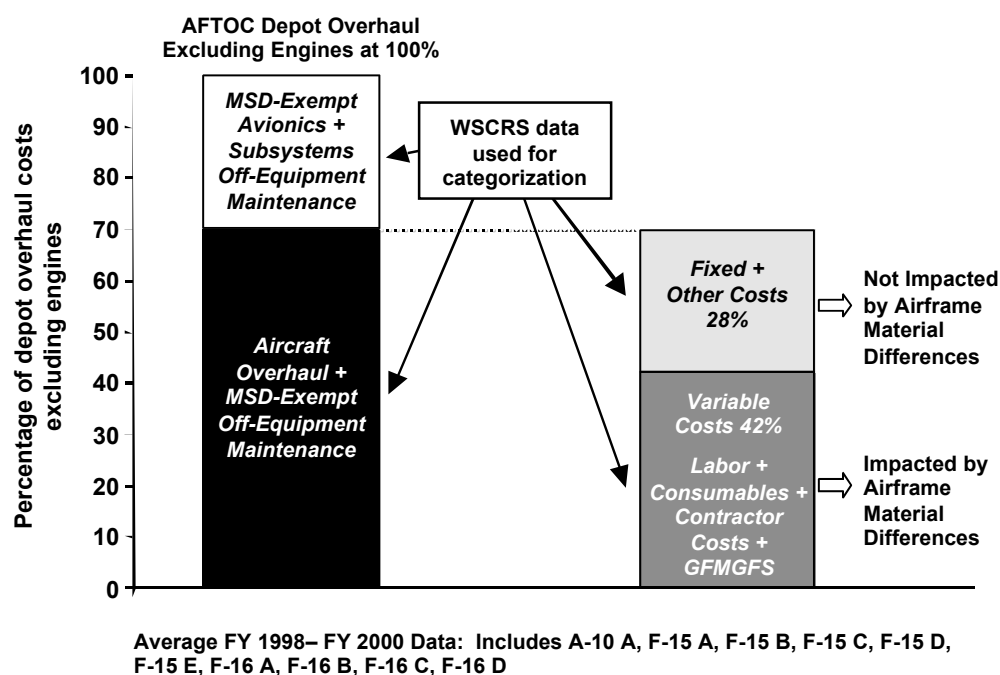


Figure B.1—Scoping the Airframe Variable Depot Costs

³ The “Other” costs categorized with fixed costs in Figure B-1 include the cost of per diem and travel expenses incurred in support of mission TDY. It also includes the cost of contract services performed in support of organic workloads. This includes contract support services only; it does not include contract depot-level maintenance costs.

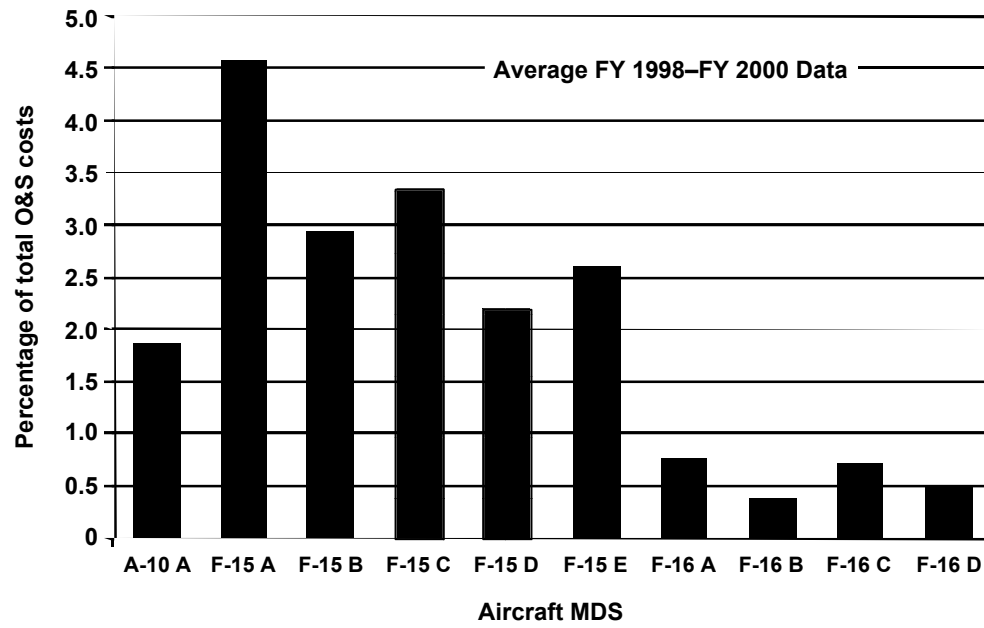


Figure B.2— Airframe Variable Depot Costs Are Less than 5 Percent of Total O&S Costs

APPENDIX C

DATABASE SOURCES FOR AIRFRAME O&S COSTS

We investigated a number of databases to obtain airframe operating and support costs. This appendix contains a listing of the available cost data related to airframe maintenance for each database we used, along with related Web sites for additional information.¹

AIR FORCE DATABASES

Air Force Total Ownership Cost

The AFTOC database is supported by the Air Force Cost Analysis Agency and provides operating and support costs by fiscal year in the CAIG format for Air Force platforms by mission design series (MDS). The CAIG format data are obligations listed for the given fiscal year in then-year dollars. The costs of DLR items corresponding to the airframe structure are listed in the “Commodities” section of this database.

Additional information is available at <https://aftoc.hill.af.mil>.

Reliability and Maintainability Information System

The REMIS database is supported by Air Force Materiel Command (AFMC) and provides base-level maintenance manhour-per-flying-hour data by WUC for the Air Force platforms by MDS. This data is updated on a monthly basis. Corrosion-prevention activities are categorized under WUC 02, scheduled inspection under WUC 03, and special inspection under WUC 04. Maintenance manhour-per-flying-hour data corresponding to the airframe are categorized under WUC 11, which is at the two-digit level. Airframe part-level maintenance data are available at the five-digit WUC level. Higher levels provide maintenance data at more-aggregated levels of assembly with WUC 11 at the two-digit level representing the whole airframe.

Additional information is available at <https://remisweb.wpafb.af.mil>.

Weapon System Cost Retrieval System

The WSCRS database is supported by AFMC and provides depot maintenance expenditure data by fiscal year for Air Force platforms by MDS. It provides cost data on

¹ Some defense sites listed in this appendix are password protected.

aircraft overhaul, engine overhaul, and MSD-exempt off-equipment maintenance of airframe, avionics, subsystems, and propulsion systems. The cost data are broken down into labor, consumable materials, contractor costs, GFMGFS, fixed investment costs, and other costs that include travel-related expenses of depot personnel.

Additional information is available at <http://www.afmc-pub.wpafb.af.mil/HQ-AFMC/FM/WSCRS/index.htm>.

NAVY DATABASES

Visibility and Management of Operating and Support Costs

The VAMOSC database is supported by the NCCA. It provides operating and support cost data by fiscal year in the CAIG format as well as in the aviation type/model/series report format, which includes noncost elements such as flying hours, aircraft age, and aircraft number. The Naval Aviation Maintenance Subsystem Reporting database, which is part of the VAMOSC database, provides airframe maintenance manhour-per-flying-hour data, cost of consumables, and AVDLRs for an airframe from the two-digit WUC level up to the seven-digit WUC level. Airframe part-level maintenance data is available at the seven-digit WUC level. Higher WUC levels provide maintenance data at more-aggregated levels of assembly with WUC 11 at the two-digit level representing the whole airframe. Corrosion-prevention activities are categorized under WUC 04 and general inspection under WUC 03. These data sets are updated yearly.

Additional information is available at <http://www.navyvamosc.com>.

Equipment Condition Analysis

The ECA database is supported by NAVAIR 3.0 Logistics. It provides maintenance manhour-per-flying-hour data from the two-digit to the seven-digit WUC level by type/model/series (T/M/S) of the aircraft. The data are updated monthly. This database provides the longest stretch of historical maintenance data, dating back to January 1, 1985.

Additional information is available at <https://www.nalda.navy.mil>.

Logistics Management Decision Support System

The LMDSS database is supported by NAVAIR 3.0 Logistics. It provides maintenance manhour-per-flying-hour data, cost of consumables, and AVDLRs from the two- to seven-digit WUC level by T/M/S of the aircraft. These data are updated monthly. The database provides maintenance data corresponding to the previous two years.

Additional information is available at <https://www.nalda.navy.mil>.

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