



**FUEL SAVINGS THROUGH AIRCRAFT MODIFICATION:
A COST ANALYSIS**

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AFIT/IMO/ENS/09-07

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 10 JUNE 2009
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Abstract

The 2008 National Defense Authorization Act requires the Secretary of the Air Force to task a federally funded research and development center to conduct an engineering analysis on modifying KC-135R and KC-10 tanker aircraft with winglets and submit a report to the congressional defense committees by May 1, 2009. This research summarizes the main issues that decision-makers should consider in the investment in a winglet modification program. The factors that should be included in any decision, such as fuel costs, aircraft utilization, and life-cycle costs are enumerated.

Using historical flight data from AMC's Global Decision Support System-2 and fuel reports from one of AMC's super tanker wings, a cost-benefit analysis is developed to aid in the decision-making process. Although the addition of winglets to the KC-135R could reduce the future fuel expenditures between \$177 million and \$1.1 billion over the modification costs by 2042, the second-order effects to current infrastructure may diminish any potential savings achieved by the modification. Further analysis is required on a location-by-location basis to obtain the actual costs of these second-orders effects before any modification decision is made.

Dedication

For Jen and Noelle

Acknowledgement

This project would not have been possible without the unwavering support of my wife Jen. Through the course of the ASAM school year, she has taken care of all possible mundane details of our lives while educating our daughter, allowing me to enjoy huge blocks of uninterrupted time for study for classes and composing this research. Words cannot express the gratitude that I have for her and all that she does.

I am also grateful for the time and guidance that Dr. James Moore, my AFIT advisor, and Dr. Donald Erbschloe, my sponsor from HQ AMC, offered during the course of the year. The information, direction and feedback they provided was critical in completing this research in a timely manner.

Many thanks are due to my friend Lt Col Phil Heseltine, an ASAM alumnus of 2007. It was the discussions we had at the beginning of the year along with the “Area for Further Research” of his ASAM graduate research project that the idea of this research was solidified. He also provided relevant information as they developed at the Joint Staff level though the year.

Finally, I would like to thank Col Jim Vechery and the support and access, as well as the information provided by the outstanding members of Team McConnell. The data set of recent tanker sorties allowed this research to be applied with relevant information in order to substantiate the hypothesis.

Ray P. Matherne, Major, USAF

Table of Contents

	Page
Abstract	iv
Dedication	v
Acknowledgements	vi
Table of Contents	vii
List of Figures	ix
List of Tables	x
I. Introduction	1
Background	2
Research Focus	4
Research Objectives/Questions/Hypotheses	5
Methodology	5
Assumptions and Limitations	6
Implications.....	6
II. Literature Review	8
History and Development	10
General and Commercial Aviation Applications	14
Application of Winglets on Military Aircraft	28
Winglets and the KC-135.....	31
III. Methodology	35
Data Sources	35
Data Format	36
Fuel Use and Cost: Past, Present and Future	37
Cost-Benefit Analysis	42

	Page
IV. Results.....	47
Results of Analysis	47
<i>Question 1, Winglet to Increase Efficiency</i>	47
<i>Question 2, Cost Effectiveness</i>	49
Implications.....	53
V. Discussion	54
Second-Order Effects.....	54
Alternative Fuel Conservation Initiatives	55
Areas for Further Study	57
Conclusion	57
Appendix A: McConnell AFB KS Sortie Data Set Summary	59
Appendix B: Abbreviations	61
Bibliography	62
Vita.....	67

List of Figures

	Page
Figure 1: A Common Wingtip Modification is the Winglet.....	8
Figure 2: Drag Components during Flight.....	9
Figure 3: Graphic Depiction of Wingtip Vortices	10
Figure 4: Vortex Fringe Example	11
Figure 5: NASA KC-135 Test Flight.....	14
Figure 6: Hawker 800XP Fuel Saving with Winglets	18
Figure 7: Hawker 800XP Range Comparison with Winglets	18
Figure 8: Winglet Technology's Citation X Elliptical Winglet.....	19
Figure 9: B-737 Comparison With/Without Winglets.....	21
Figure 10: B-767 Comparison With/Without Winglets.....	24
Figure 11: Airbus A320 with Tip Fence	25
Figure 12: Effect of Winglets on Range Performance.....	33
Figure 13: US Government Fuel Consumption	39
Figure 14: Distribution of Air Force Fuel Usage.....	40
Figure 15: The 40-Year Tanker Recapitalization Plan	45
Figure 16: Potential Annual Savings under Option A	52
Figure 17: Potential Annual Savings under Option B	52
Figure A1: Number of Sorties by Type	59

List of Tables

	Page
Table 1: Summary of Winglet Benefits	26
Table 2: Sample of GDSS-2 History Report for McConnell AFB, KS	36
Table 3: Sample of McConnell AFB Fuel Data Report Submitted to HQ AMC	38
Table 4: DESC Contracted JP-8 Fuel Cost	41
Table 5: Commercial Transport Aircraft Winglet System List Prices.....	43
Table 6: Descriptive Statistics on Reported and Potential Fuel Burn Rates.....	48
Table 7: Average Break-Even Point for Each Year's Modification	50
Table 8: Average Break-Even Point of All Modifications	50

FUEL SAVINGS THROUGH AIRCRAFT MODIFICATION: A COST ANALYSIS

I. Introduction

If you gave us money for jet airplanes, I would buy tankers, not airplanes for MATS [Military Air Transport Service, ancestor of Air Mobility Command]...I think we would increase our combat capability more in that manner (Cohen, 2001).

-- General Curtis E. LeMay
Commander in Chief
Strategic Air Command
October 1948 – June 1957

Look at the headlines in recent newspapers. “Rising Diesel and Jet Fuel Prices Starting to Weigh on Economy” (Mouawad and Bajaj, 2005). “Oil Sets New Trading Record Above \$147 a Barrel” (Read, 2008). “Carriers Slash US Capacity” (Boehmer, 2008). “Deflated by Oil Price’s Dive” (Mufson and Pan, 2008). These headlines, along with many others, are confirmation that the crude oil market and therefore jet fuel prices are extremely volatile. This volatility makes it very difficult for corporations and government entities to budget their operating expenses. Companies within the aviation industry must find ways to reduce cost and remain profitable; otherwise, they will be forced into bankruptcy. They will become a footnote in history.

Go to any airport and you will find an element which is common to most airline companies in the public sector. Yes, ticket costs are rising and on-board service is marginal at best but, with most airlines, there is yet another common concept with their airframes...winglets. New aircraft are now being designed with winglets, but when companies, such as Southwest Airlines and others, invest millions upon millions of

dollars in retrofitting their older aircraft, this validates their belief in the value of the concept. After all, corporations do not do anything unless it positively affects their bottom line.

Moving to the public sector, the Energy Bulletin reports that the Department of Defense (DoD) is the largest oil consuming government body in the US and in the world (Karbuz, 2006). The US Air Force (USAF) is the largest consumer of oil within the DoD. And Air Mobility Command (AMC) is the largest consumer of oil within the USAF. Therefore, since the USAF has over 400 KC-135R aircraft within AMC and other major commands, any fuel savings achieved by modifying the KC-135R with winglets would positively affect AMC, the USAF, the DoD, as well as the US government as a whole. With increasing operational costs and limited defense budgets, it is more important than ever that Air Force professionals find ways to balance their operational requirements and their fiscal responsibilities as stewards of the tax-payer's money.

Background

The oil embargo of the early 1970s was a catalyst for organizations in the aviation industry to begin researching methods to reduce fuel consumption by improving the efficiency of their aircraft and engines. Of note, some of these industry leaders included Boeing, Pratt and Whitney, as well as commercial airlines. These approaches took on many forms such as engine design, aerodynamic performance, and gross weight considerations. While the engine efficiency of aircraft has steadily improved and operating procedures have changed to lower the aircraft operating weights in recent years, additional measures are continually being pursued. With the recent oscillation in

fuel costs, the DoD continues to search for methods to lower fuel expenditures. This emphasis has also made its way into the language of the House Armed Services Committee (HASC) Report 110-652 of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2008:

The committee commends the Air Force for its efforts to increase aircraft fuel efficiency and decrease fuel consumption. The committee notes that initiatives such as re-engining aircraft, modifying in-flight profiles, and revising aircraft ground operations contribute to decreased fuel consumption and increased life-cycle savings.

The committee is aware that winglet technology exists for aircraft to increase fuel efficiency, improve take-off performance, increase cruise altitudes, and increase payload and range capability. The committee notes that winglets are currently used on commercial aircraft and result in a five to seven percent increase in fuel efficiency. The committee believes that incorporating winglets on military aircraft could increase fuel efficiency on certain platforms and that the Air Force should examine incorporating this technology onto its platforms.

The committee directs the Secretary of the Air Force to task a federally funded research and development center to conduct an engineering analysis on modifying KC-135R and KC-10 tanker aircraft with winglets and submit a report to the congressional defense committees by May 1, 2009. For the engineering analysis and report, the Secretary of the Air Force shall: use current performance data for each aircraft; include a cost comparison analysis for the cost of winglet modifications compared to the return on investment realized over time for each aircraft during its programmed service-life; determine the market price of JP-8 aviation jet fuel at which incorporating winglets would be beneficial for each aircraft mission design series; assess all positive and negative impacts to aircraft maintenance and flight operations; and analyze investment strategies the Air Force could implement with commercial partners to minimize Air Force capital investment and maximize investment return.

In recent years, there has been a surge in the utilization of winglets in response to the results of various types and levels of studies that have been performed since the 1970s. The concept of winglets modification and design has been validated by the National Aeronautics and Space Administration (NASA), aircraft manufactures such as Boeing and Airbus, as well as the United States Air Force Academy (USAF). In

addition to the HASC directive, this study reviews the effectiveness of winglets and conducts a cost analysis of modifying the KC-135R with winglets.

Research Focus

There were a multitude of ramifications to consider when analyzing the idea of adding winglets to the KC-135R. Utilizing a macro to micro approach, this research began by analyzing winglets as a concept on all aircraft. With the concept proven to be a valid approach for improving aircraft efficiency, winglets on large transport aircraft were the next focus. Again, with the concept demonstrated to be compelling as witnessed by the emergence of winglets in the commercial aviation industry, the spotlight then shifted to using winglets on military aircraft and specifically modifying the KC-135R with winglets.

With the performance and efficiency justified, the costing aspect had to be addressed. The fuel cost for operating the aircraft was considered, along with taking into account the potential fuel cost in future years. This was used to develop the best case, worst cast, and most likely case scenarios for fuel cost, which was a key aspect in the cost analysis.

Since winglets have increased aircraft efficiency, the cost of modifying the aircraft as compared to the fuel savings achieved from the modification was reviewed. Aside from the cost of modifying the aircraft with winglets, the research analyzed the total cost of winglets, to include cost/saving break-even points, potential future savings, and life cycle estimations of the KC-135R. Additionally, the potential second-order effects were also considered such as hangar requirements for increased wingspan, parking

space issues with assigned aircraft, winglet maintenance, and Air Force aircrew and maintenance personnel training.

Research Objectives, Research Questions and Hypotheses

The overall objective of this research was to identify ways to reduce the total cost of operating the KC-135R by the addition of winglets, thus benefiting the USAF and the American tax-payer. The research questions addressed with this research were:

1. Are winglets a valid way of decreasing the fuel burn rate, thus increasing the aircraft range and endurance (or efficiency) of the KC-135R?
2. Is modifying the KC-135R with winglets a cost-effective method of reducing the operating costs for the aircraft and the USAF?

Derived from these questions, the research hypothesis was as follows:

Modifying the KC-135R with winglets will increase the fuel efficiency in a majority of the aircraft flight regimes and provide a beneficial return on investment.

Methodology

During the research, a spreadsheet model was developed using Microsoft Excel 2007[®]. This model analyzed the potential savings that would be possible for KC-135R sorties with the modification of winglets. With the data available from the actual flights of all sorties flown in the fourth quarter of FY2008 at McConnell Air Force Base (AFB) Kansas (KS), to include local training sorties and operation missions, the model accounted for the various flight regimes of the KC-135R. Considered “the” super tanker wing for the USAF, McConnell AFB executes the complete range of all missions in

which the KC-135R is used. This sample provided a representative cross-section of KC-135R missions as a whole.

Additionally, the research developed a second model, again using Microsoft Excel 2007[®], to estimate future fuel cost using historical data from Defense Energy Support Center (DESC). Although, like stock market analysis, past performance (previous fuel contract rates) does not guarantee future returns (future fuel contract rates), this model gave a realistic and conservative estimate of future prices which aided in the best case, worst case, and most likely case scenarios analyses.

Assumptions and Limitations

The focus of this research was primarily on the KC-135R. However, because of the assumed benefit of winglets in general, winglet modification would likely be applicable to all large mobility-type aircraft in the USAF inventory with similar wing designs that are not currently fitted with winglets, e.g. KC-10, E-8 and the like. Due to the lack of a KC-135R test platform modified with winglets, this study was limited to a compilation of test results from the 1970s and 1980s based on a KC-135A modified with winglets as well as various wind tunnel tests on KC-135R scale model aircraft.

Implications

The implications of modifying the KC-135R with winglets are significant. Assuming that the aircraft is 4 to 5 percent more efficient with winglets than without, this modification has the potential to increase range by 176 miles and endurance by 52 minutes in a normal training or operational mission. By implementing this modification, the fuel savings are equivalent to \$1,087 and \$2,212, respectively per mission, using FY2009 DESC fuel prices current as of October 1, 2008. These per-mission cost savings

could potentially translate to an estimated Air Force wide yearly savings between \$258 million and \$526 million, as found in a recent study by the USAFA (Halpert and Prescott, 2008). These savings could be used in a variety of ways.

As previously stated, the central focus of this research is the examination of modifying the KC-135R with winglets from a cost analysis perspective. The remaining portions of this research are broken down into four main sections. Chapter 2 is the Literature Review which focuses on previous research and flight testing of winglets on various aircraft, both commercial and military. Chapter 3, Methodology, describes the approach used to address the research questions, in addition to past, present and future fuel expenditures. Chapter 4, Results, discusses the results of each question individually, while reviewing the output of the Microsoft Excel 2007[®] models. Lastly, Chapter 5, Discussion, concludes the paper by discussing second-order effects of the winglet modifications, alternative energy conservation strategies, as well as suggestions for potential future research efforts.

II. Literature Review

I shall proceed from the simple to the complex. But in war more than in any other subject we must begin by looking at the nature of the whole; for here more than elsewhere the part and the whole must always be thought of together.

-- Karl von Clausewitz
On War, Book One, Chapter One
Prussian Soldier, Military Strategist
July 1780 – November 1831

Winglets are defined as the small, nearly vertical, aerodynamic surfaces which are designed to be mounted at the tips of aircraft wings as shown in Figure 1 (Barber and Selegan, 1981). Winglets are a subset of wingtip modifications, which include wingtip extensions, raked wingtips, blended and canted winglets, up/down winglets, and wingtip fences, to name a few. While each of these wingtip designs benefits specific performance factors of various aircraft, the motivation behind most wingtip devices is to reduce induced drag. In an effort to narrow the scope, this research focused solely on the application of winglets, while excluding all other modification designs.



Figure 1: A Common Wingtip Modification is the Winglet (via APB)

The purpose of winglets is to improve aircraft efficiency by reducing the strength of the wingtip vortices. This is accomplished by introducing a physical constraint in the normal airflow field. The winglet functions by relocating the wingtip vortices above and outward from their normal location. The relocated vortices become considerably smaller, thereby reducing the induced drag and decreasing the fuel burn. Additionally, winglets improve the span load distribution of the wing without excessively increasing the wing span, thus increasing the efficiency of the wing (APB, 2007). Winglets also have the potential to reduce overall drag, increase lift, improve safety, improve roll performance and provide increased stability, depending on the winglet design.

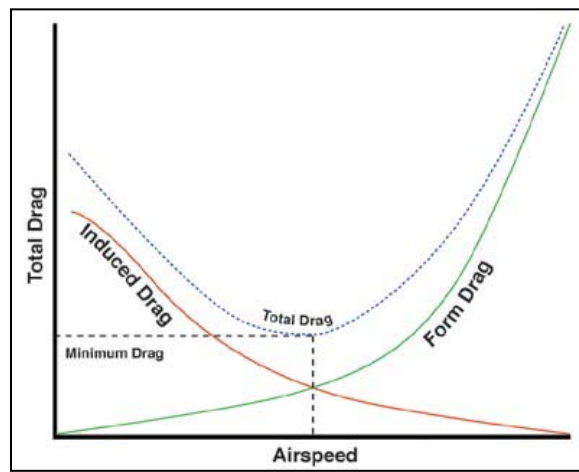


Figure 2: Drag Components during Flight

Induced drag is one of several drag components that affect aircraft during flight as seen in Figure 2. Drag is the aerodynamic force that opposes an aircraft's motion through the air. It can be divided into the following categories: parasitic drag, wave drag and induced drag. Parasitic drag, consisting of form drag, skin friction drag and interference drag, is caused by moving a solid object through a fluid. Form drag is primarily caused by the air that flows over the aircraft, leading to pressure differences in the wake. Skin

friction drag is caused by the actual contact of air particles against the surface of the aircraft. Interference drag is due to the interaction between the various parts of the aircraft, such as the engines, the wing and the external fuel tanks, or the wing and a winglet. Wave drag, as a form of pressure drag, only occurs at supersonic flight and therefore is not a factor in this study. Finally, induced drag or drag due to lift, is produced by the generation of three-dimensional airflow characteristics near the aircraft's wingtip. As the flow encounters the wingtip shape, it rolls up over the tip side edge resulting in the well-known trailing vortices displayed by lifting wings (see Figure 3). The resulting induced drag can be extremely large for certain aircraft wing configurations, especially under high-lift, low-speed flight conditions (Chambers, 2003).

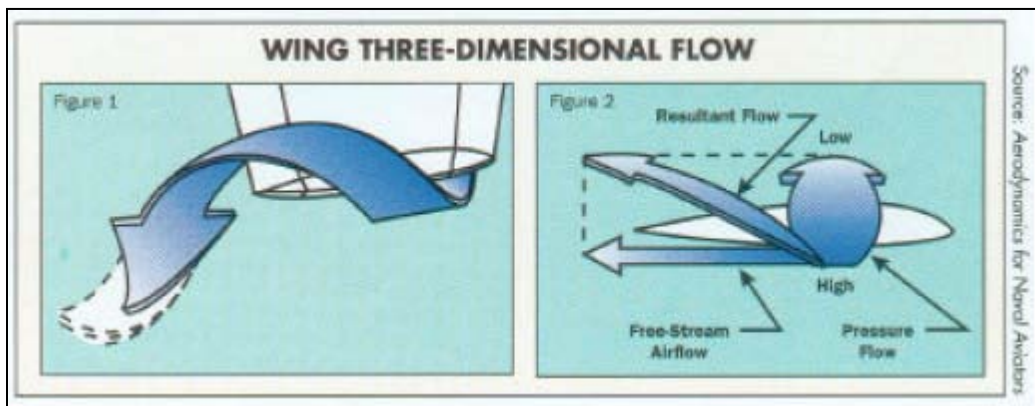


Figure 3: Graphic Depiction of Wingtip Vortices

History and Development

The concept of winglets was originally developed in the late 1800s by a British aerodynamicist, Frederick W. Lanchester (Eickmann et al., 2007). Early studies by Dr. Lanchester and others in England indicated that vertical surfaces located at the wingtips could significantly reduce the three-dimensional effects and thereby reduce induced drag (Chambers, 2003). In 1897, a patent was obtained by Dr. Lanchester for the concept of

vertical endplates at the wingtips (Whitcomb, 1976). In 1907, he published a book titled *Aerodynamics* where he outlined the circulation theory of lift and, for the first time, discussed the effect of wingtip vortices on finite-wing aerodynamics (Anderson, 2004). Dr. Lanchester's theory of wingtip vortices was explained with the example of a horizontal plane supporting a weight that is allowed to fall vertically. As shown in Figure 4, he described that with these conditions "...there is a circulation of air around the edge of the plane from the under to the upper side, forming a kind of vortex fringe..." (Lanchester, 1907). This led to further interest on the subject by others in Germany.

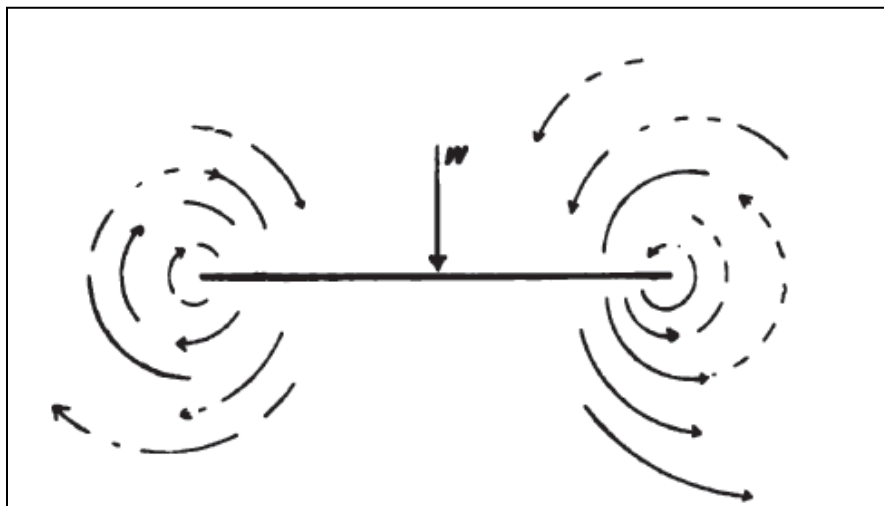


Figure 4: Vortex Fringe Example (Lanchester, 1907)

Expounding on the work of Lanchester, Ludwig Prandtl began to study the effects of induced drag. As a professor of applied mechanics at Göttingen University in Germany, Dr. Prandtl developed the boundary-layer concept, where it became possible to quantitatively calculate aerodynamic drag (Anderson, 2005). He worked with Dr. Max Munk for almost ten years to solve problems related to induced drag. The result was his lifting line theory, which enabled accurate calculations of induced drag and its effects on lift (Johnston, 2008).

Following the earlier works of Dr. Prandtl, a number of theoretical analyses have indicated the significant improvements possible with non-planar wing designs including vertical surfaces at the tip. On the basis of these encouraging theoretical studies, a number of experimental investigations of various end plates at the wing tips have been made (Whitcomb, 1976). Dr. Munk continued to improve on and add to the earlier theories of aerodynamics. While employed at the National Advisory Committee for Aeronautics (NACA), he proposed the development of the new Variable Density Tunnel (VDT), as well as publishing several papers detailing new methods for calculating lift, load distributions, and pitching moments of wings (Eckert, 2006). In subsequent studies at NACA during the late 1930s, the lift distribution of wings with end plates were studied and it was discovered that moving an end plate of a certain length up from the symmetrical position would result in a slight increase in the total lift (Mangler, 1938). In the 1950s, Richard Vogt received a patent from the US Patent Office for his design of twisted wing tip fins for airplanes. In his patent, Vogt described that by twisting the wing tip fin to a favorable angle of attack, the energy of the wing tip vortex would produce a forward thrust on the wing (US Patent Office, 1951).

Continuing with the idea of minimizing induced drag, the idea of winglets was later refined in the 1970s by Dr. Richard T. Whitcomb, an aeronautical engineer at the NASA Langley Research Center. Following his development of the Area Rule and the supercritical airfoil, he refined the idea of winglets. Inspired by an article in *Science Magazine* on the flight characteristics of soaring birds and their use of tip feathers, Dr. Whitcomb focused on the wingtip flow dynamics associated with induced drag (Chambers, 2003). He designed a winglet using advanced airfoil concepts integrated into

a swept, tapered wing shape that would interact with the wingtip airflow and circulation to reduce drag (Eickmann, 2007). Dr. Whitcomb validated the usefulness of winglets with wind tunnel tests and computer studies. His winglet designs are the direct predecessor to what is seen today on many aircraft designs.

Successive to Dr. Whitcomb's research, multiple studies were completed to confirm his winglet findings. Researchers at the Langley Research Center showed that a winglet provides a greater gain in induced efficiency when compared to a wingtip extension (Heyson et al., 1977). These studies also provided proof that a winglet shows the greatest benefit when wing loads are heavy near the wingtip. Additionally, the research found that under these conditions, low-speed performance is enhanced to a greater extent than during a cruise condition. From these experimental tests, it was demonstrated that winglets could significantly improve the efficiency of transport aircraft. The test also provided general guidelines for the design of winglets (Heyson et al., 1977).

Subsequent to these wind tunnel tests and computer studies, actual flight tests were accomplished on several large transport-sized aircraft. Dr. Whitcomb predicted that aircraft equipped with winglets would realize improved cruising efficiencies of between 6 percent and 9 percent (Whitcomb, 1976). To obtain actual data on full-scale aircraft, a winglet flight test program at the NASA Dryden Flight Research Center occurred in 1979-80. The USAF furnished a KC-135 test aircraft (see Figure 5), a militarized version of the Boeing 707 aircraft, to Dryden in late 1977 in a joint program with NASA, Boeing, and the USAF. The program's first test flight occurred in July 1979 followed by 47

additional test flights. Results of the flight test on the aircraft recorded an increased fuel mileage rate of over 6 percent, validating Dr Whitcomb's earlier research (NASA, 2004).



Figure 5: NASA KC-135 Flight Test

Additionally, the Douglas Aircraft Company conducted other aircraft studies for NASA in 1978 to 1979 under the Aircraft Energy Efficiency Program; one of them involving wind tunnel tests of winglets on the DC-10 aircraft, another on the application of a complete wing/winglet system to a hypothetical advanced commercial airliner (Haggerty, 1994). Both studies showed that significant performance gains could be realized with the addition of winglets, in particular reduced fuel consumption. Later in 1982, NASA and the Douglas Aircraft Company cosponsored a flight test program of a DC-10 aircraft fitted with winglets and once again found that a winglet modification offered a measurable improvement in fuel consumption (Haggerty, 1994). These results directly lead to the inclusion of winglets on the MD-11 aircraft design a few years later.

General and Commercial Aviation Applications

The development of winglets is one of the most successful examples of a NASA aeronautical innovation being utilized on all types of aircraft around the world (NASA,

2004). In the on-going process to improve the performance of modern sailplanes, the efforts of recent test and design studies have resulted in a measurable increase of aerodynamic capability in these aircraft. Sailplanes must perform effectively in various flight conditions in order to be efficient. In a cross-country flight scenario, a sailplane must be able to climb effectively in thermals, as well as be able to glide efficiently between the thermals at high speeds (Maughmer et al., 2001). In order to provide the pilot with the most performance through all phases of flight, a successful design must balance the conflicting situations of cruise conditions and climbing in thermals. To improve the performance of sailplanes, efforts have been ongoing since the 1980s to incorporate winglets in sailplane designs (Maughmer et al., 2001).

Although performance gains achieved with winglets are only a few percent, such small differences can be important in determining the outcome of many cross-country flights and contests. For example, in the 1999 US Open Class Nationals, just 68 points separated first place from sixth place. This difference amounted to less than 1.5 percent - far less than the performance advantage that can be achieved by using well designed winglets (Maughmer, 2002). Since that time, from initially being able to do little to improve overall sailplane performance, winglets have developed to such an extent that few gliders now leave the factories without them (Maughmer, 2006).

The most aggressive initial use of winglet technology came from within the general aviation and business jet community. In 1974, before Dr. Whitcomb published his general design approach to winglet design, the first aircraft to fly with winglets was the propeller-driven Vari-Eze designed by Burt Rutan (Chambers, 2003). The Vari-Eze was a light homebuilt aircraft that incorporated control surfaces on the winglets for

rudder control. When combined with other advanced design features, winglets were credited with helping the Vari-Eze to achieve an efficiency world-record in 1975 in the under-500 kg class. Now the majority of homebuilt aircraft coming out of hangars around the world utilize winglets of varying designs.

Over the years, winglets have made their presence felt in other general aviation aircraft. RAM Aircraft has engineered and flight test certified winglets for Cessna 414A and 421C aircraft. According to the RAM Aircraft website, these modifications increase high altitude speed and climb performance. Additionally, other benefits achieved with winglets include increased high altitude range, fuel savings, speed, and stability. BLR Aerospace has also developed a winglet system for the Beechcraft King Air B200 series aircraft. According to the BLR Aerospace November 2, 2005 news release and the winglet brochure, the BLR winglets system is designed to reduce drag, reduce fuel burn by 3.5 percent, increase cruise speed by three to six knots and increase vertical rate of climb by 300 feet per minute while improving handling qualities.

However, winglets have not been readily adopted as a common design practice by all aircraft manufacturers. Some anti-winglet advocates, such as Cessna Aircraft Company and Dassault Aviation, were originally opposed to such non-traditional modifications to their planar wing designs. They claimed that a properly designed wing needs no such devices and that it offers better performance over a wide range of speed, load and lift conditions (Andre, 2000). Additionally, critics noted that that bent wings are more expensive to manufacture than flat wings and doubted if they were worth the trouble. However in recent years, both Cessna and Dassault have joined the growing number of winglet users.

The use of winglets throughout the aviation industry in the US and overseas is constantly growing (NASA, 2004). Around the time of Dr. Whitcomb's studies Learjet released their exciting new test-bed aircraft at the National Business Aircraft Association convention in 1977 (Chambers, 2003). Although originally intended as an experimental prototype aircraft, the corporate-size Learjet Model 28 became the first commercial aircraft to use winglets, due to its impressive performance with winglets compared to without. Flight tests comparing performance with and without winglets showed that the winglets increased range by about 6.5 percent and also improved directional stability (Chambers, 2003). Gulfstream Aerospace also has aggressively studied the application and incorporation of winglets in its line of business jets. In 1981, the Gulfstream G1159 was introduced, which was a modified G1154 with G1159 wings along with incorporated winglets. The incorporation of winglets continued on the Gulfstream III, the Gulfstream IV, and the Gulfstream V. The spectacular performance of the Gulfstream V extended its operational range to over 6,500 nm and led to over 70 national and world flight records (Chambers, 2003). Now, several decades later, winglets are incorporated into the designs of many other business jets.

Retrofitting winglets to existing business jets is also a fast-growing market within the aviation industry itself. Many winglet marketing firms report their products help increase aircraft roll rates and lower approach and takeoff speeds. One such company, Aviation Partners Boeing (APB), began in 1991 as Aviation Partners, Inc. (API), by Mr. Joe Clark and Mr. Dennis Washington with the goal of becoming the leader in the design, production, and marketing of an advanced technology winglet system. Aviation Partner's Blended Winglet™ validates the earlier studies from Dr. Lanchester to Dr. Whitcomb by

reducing the wingtip vortex, resulting in less drag, lower fuel burn rates, and superior climb and cruise performance. The Raytheon Aircraft Company, in conjunction with APB, is manufacturing winglets for the Hawker 800 series aircraft. When asked for the reason people want the addition of winglets, James E. Schuster, Chair and CEO of the company, said that it is because of “the performance benefits that you get on the airplane—fuel, speed, range, etc.”(Piazza, 2006) (see Figure 6). Additionally, winglets on the Hawker reduce drag by over 7 percent, increasing the range between 180 – 200 nm, or between 25 and 30 minutes, with no added fuel (Norris, 2004) (see Figure 7).

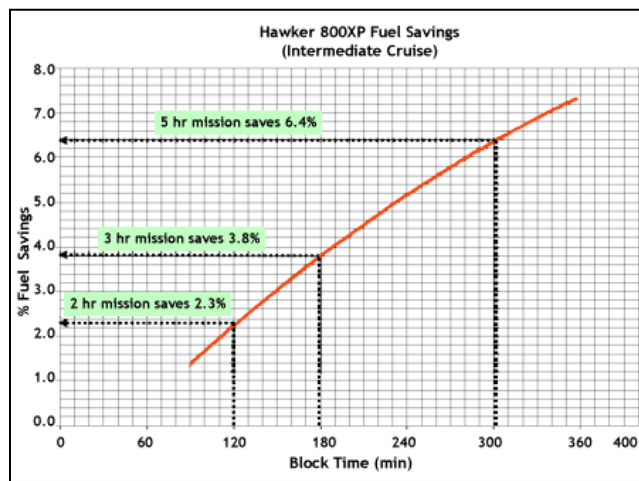


Figure 6: Hawker 800XP Fuel Saving with Winglets (via API)

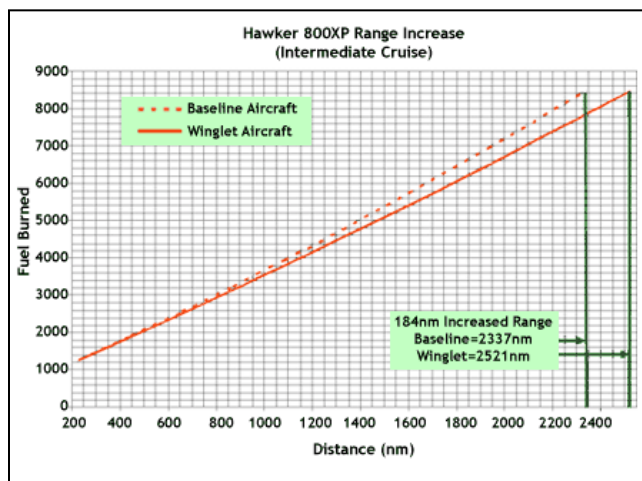


Figure 7: Hawker 800XP Range Comparison with Winglets (via API)

APB is not the only company retrofitting business jets. Winglet Technology LLC, a company that provides products and services to manufacturers for both business jets and transport category aircraft, has collaborated with Cessna Aircraft Company to retrofit Winglet Technology's patented Elliptical Winglet™ design on Cessna's Citation X series aircraft. According to Winglet Technology, Elliptical Winglets™ exhibits a significantly advanced design that minimizes induced drag and eliminates wing/winglet interference drag. This Wichita-based company has taken a new approach to winglet technology that scribes a continuous elliptically shaped curve from the point where the winglet leaves the wing to its tip as seen in Figure 8. Some performance improvements include increased cruise speeds by 15 knots, increased range by 150 nm, and improved climb performance, as well as reduced fuel burn by 5 percent. Both certification flight testing and full-scale wing and winglet static tests were completed in the fall 2008, and supplemental type certificates (STC) for the Citation X are expected in summer 2009 (Esler, 2008).



Figure 8: Winglet Technology's Citation X Elliptical Winglet

Within the commercial sector there are a number of very successful applications of winglet modifications (Eickmann et al., 2007). Following the oil crisis of the 1970s and then again in recent years, winglet modification has emerged as a method to provide commercial aviation a means to increase their operating efficiency and lower their fuel expenses. As a result of NASA's Aircraft Energy Efficiency Program at Langley Research Center, the Douglas Aircraft Company (now part of the Boeing Aircraft Corporation) tested and proved the usefulness of winglets on their DC-10 aircraft. Later to be labeled the MD-11, this was the first large commercial aircraft to incorporate winglets in its design (NASA, 2004). Entering airline service in 1991 and growing to a fleet of more than 100, the MD-11 attained the combination of a large payload (290-plus passengers) and a very long range (more than 8,200 nm) with the help of winglets (Haggerty, 1994).

The benefits of winglets continued to populate to other aircraft series as well. Part of the Boeing 7-series aircraft, the 747-400, introduced in October 1985, was the first Boeing aircraft to include winglets as part of the original design (Chambers, 2003). Specific changes from previous B-747 series included a 6-foot wingtip extension along with a 6-foot canted winglet for the purpose of improving cruise efficiency of the aircraft. Initially the Boeing engineers thought the problem of wingtip vortices could be minimized by extending the wing span. However, this was deemed not a viable solution due to possible taxi problems at crowded airports as well as limiting the number of gates with which the aircraft would be compatible. The result was the addition of winglets, which provided the benefit of extended wing spans while maintaining the number of standard airport slots. The wingtip modification resulted in a 4 percent reduction in the

C_L/C_D ratio with much of the improvement coming from the wing span extension along with a 3 percent fuel mileage improvement (Eickmann et al., 2007).

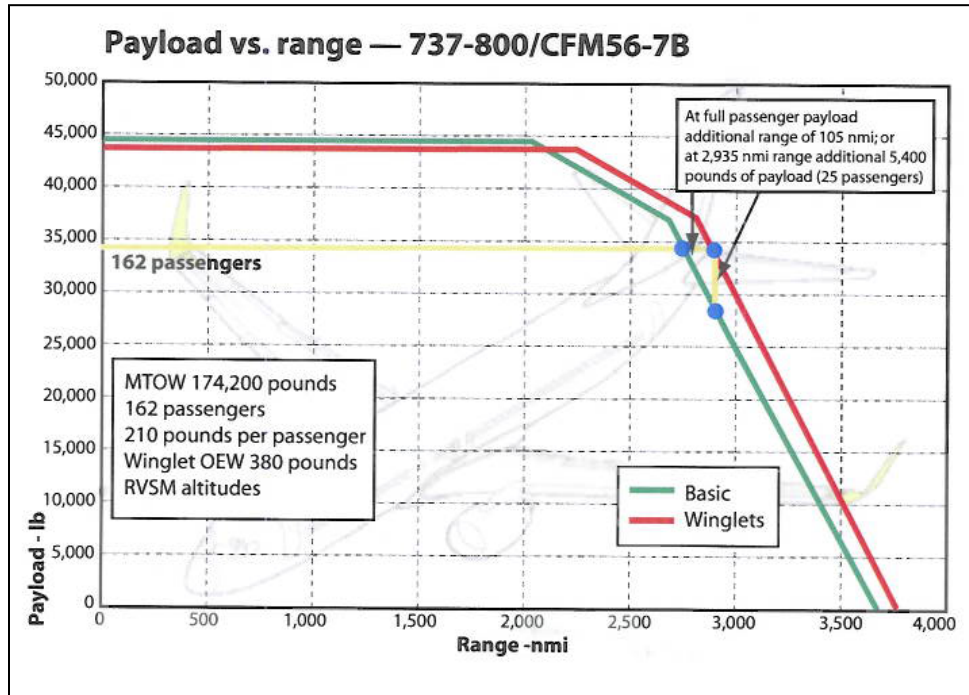


Figure 9: B-737 Comparison With/Without Winglets (via Boeing)

In addition to the B-747 application, Boeing expanded its customer options by adding winglets to its new advanced models of the 737-series aircraft. On its original release in the 1990s, the Boeing 737-NG (Next Generation) aircraft was introduced without winglets. After several years in service, a joint venture between the Boeing Business Jet (BBJ) Company and API proposed to test the Blended Winglet™ on the 737-BBJ. Developed in 1991 by API's chief aerodynamicist Dr. Bernie Gratzner, the Blended Winglet™ was designed to alleviate some of the problems with interference drag in the transition area between the wing and winglet (APB, 2007). The redesign resulted in a block fuel savings of 4 to 5 percent for 737-NG aircraft compared to 1 to 1.5 percent savings with traditional-style winglets (see Figure 9). Soon thereafter Aviation Partners

Boeing began offering Blended Winglet™ technology as retrofits or as standard production line buyer-furnished equipment options for all 737-BBJ and 737-NG aircraft (APB, 2006).

With the success of the 737-NG winglet, APB developed and certified winglet modification kits for other earlier models of the B-737 series aircraft, mainly the 737-300, -400, and -500 models. While production of these models ended in 1998, commercial and private companies currently operate more than 2,000 B-737 aircraft with decades of life expectancy remaining (Eickmann et al., 2007). The business case to modify aircraft using Blended Winglet™ technology was compelling due to the design performance being optimized at stage lengths typical to the 737-300, rather than at the maximum design range (APB, 2006). A typical 737-NG operator saves 95,000 – 130,000 gallons of fuel per aircraft per year for the entire economic life of the aircraft.

Additionally, through the reduced fuel consumption rate, a Blended Winglet™-equipped B-737 aircraft reduces carbon monoxide and nitrous oxide emissions by 4 percent and 5 percent, respectively, while decreasing the take-off noise footprint by 6.5 percent (APB, 2007). Due to the improved wing efficiency and reduced noise footprints, many Blended Winglet™ equipped operators in Europe have been able to decrease operating fees and noise surcharges by opting for lower-thrust engines and lower max take-off weight.

Positive results of B-737 winglet modification were proven by multiple airlines. In 2000, Southwest Airlines began a winglet study for its fleet to reduce fuel burn and as a method to alleviate the impact of increasing oil prices. As explained by Jim Sokol, Vice President of Maintenance and Engineering of Southwest Airlines, the 737-700 study indicated a fuel burn improvement of between 2.5 and 4 percent, depending on the flight

distance (Eickmann et al., 2007). With the success of the 737-700 program, Southwest Airlines initiated orders for its older 737-300 aircraft. Fuel burn improvements on these aircraft were similar to previous modifications. Modifying their aircraft with winglets saved them more than 27 million gallons of jet fuel in 2007 alone (Kelly, 2008). Aloha Airlines, when in operation, realized fuel savings around 5 percent on their winglet-equipped B-737 aircraft (Hine, 2004). Similar results appeared elsewhere. Alaska Airlines expected to reduce their B-737 fuel burn by 120,000 gallons or 3.5 percent per year (Marino, 2004).

Resulting from the positive experience of winglets on B-737 series aircraft, further studies were launched to evaluate the possible benefits of retrofitting the B-757 and B-767 with winglets. While the B-757 series aircraft is no longer in production, there are more than 1,000 aircraft in service with the potential for another 20 years of service life. APB was ultimately able to develop a retrofit package that uses the same winglet as the 737-NG on the B-757 aircraft. When combined with the necessary wingtip extension, the B-757 modification resulted in a block fuel savings potential of up to 5 percent, depending on mission range. Operators of Blended Winglet™-equipped 757-200 aircraft save even more than the savings seen on the 737-NG aircraft: up to 240,000 gallons per aircraft per year (APB, 2007). Comparable positive results were also found with the 767-ER winglet modification. According to John Hotard, an American Airline spokesperson, “American will conserve 17 to 21 million gallons in fuel annually for the 767-300ER fleet” (see Figure 10). Once winglets are installed on all of our current B-737, B-757 and B-767 fleets, we will be saving more than 42 million gallons of fuel per year” (APB, 2007).

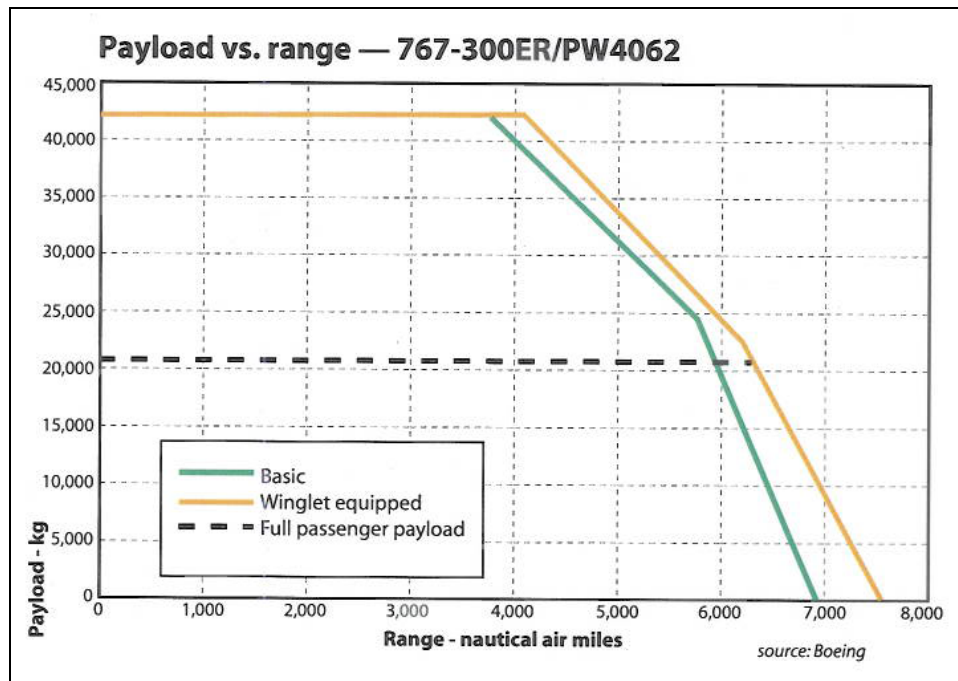


Figure 10: B-767 Comparison With/Without Winglets (via Boeing)

In the retrofit market, the Quiet Wing Corporation based in Bellevue, Washington provides winglet modifications for B-727 operators. The company was originally formed over 15 years ago primarily to provide Stage 3-compliant engine hush kits for the B-727, but offered additional modifications with other benefits to operators flying these aircraft. Peter Swift, Quiet Wing’s director of sales and marketing, explained that “Throwing the winglet modification in increases range and fuel economy by 5 and 6 percent, a significant saving with today’s fuel prices” (March, 2007). As outlined in 2004 by Phil Kirk, Quiet Wing’s director of engineering, their sales have historically been mostly overseas aircraft going to third world countries with the majority of those sales tied in with noise regulations, since they provide winglets as part of a hush kit system (Hine, 2004). One of Quiet Wing’s customers for their B-727 winglet, Amerijet International, reports that their modified B-727 aircraft achieve a 4 percent or more fuel savings. Additionally, the winglet equipped aircraft showed increased climb performance which

increased the cruise performance, as detailed by Carlo Postell, director of quality control for Amerijet International (Hine, 2004). With the useful life of the B-727 nearing, Quiet Wing also developed a winglet modification system for older B-737 aircraft in service. As described by Mr. Swift, their B-737 winglet system provides an increased payload up to 9,000 pounds, increased range up to 3 percent, fuel savings between 3 to 5 percent, along with improved take-off, landing and hot and high performance (March, 2007)(APB, 2007).



Figure 11: Airbus A320 with tip fence (via EADS North America)

The incorporation of winglets in large commercial aircraft is not limited to domestic manufacturers. Airbus Industries, the aircraft-manufacturing subsidiary of EADS (a European aerospace consortium), produces around half of the world's jet airliners. Within their aircraft line, two types of wingtip devices are present: the wingtip fence found on the A310, A320, and A340 (see Figure 11), while the A330 and A380 were designed with a highly swept winglet similar to those found on the 747-400. The wingtip fence can be described as a small dual-winglet configuration that is highly swept with nearly vertical upper and lower partial-chord winglets. The wingtip fence was first

used in 1985 on the A310-300 as a drag-reducing device to improve fuel efficiency. The winglets reduced the lift-induced drag on the aircraft, bringing cruise fuel savings of 1 percent for the A300 and 1 to 5 percent for the A310 (FI, 1985). For both the A310 and A320, the size of these winglets indicates that their purpose was to take advantage of structural margin in the wings, since both aircraft were initially certified with plain wingtips (Eickmann et al., 2007). Michael Smith, Airbus’s engineering product manager for research and technology, specified that their wingtip fences affect aerodynamic benefits at both high and low speeds. They add aerodynamic efficiency during cruise and at low speeds, resulting in improved mission performance notwithstanding the increase in overall weight and wing loads (Fitzsimons, 2005). A summary of the benefits winglets provide to the various aircraft discussed is detailed in Table 1.

Table 1: Summary of Winglet Benefits to Various Aircraft

Aircraft	Winglet Benefits Summary					Source
	Fuel Burn Rates	Range	Cruise Speed	Climb Rate	Drag	
Sailplanes					-10%	Maughmer, 2002
Beech King Air	-3.5%		+ 3 to 6 knots	300 fpm		BLR Aerospace website
Learjet Model 28		+ 6.5%				Chambers, 2003
Gulfstream V		to over 6,500 nm				Chambers, 2003
Hawker 800		+ 180 to 200 nm			-7%	Norris, 2004
Citation X	-5%	+ 150 nm	+ 15 knots	increased		Winglet Technology website
MD-11		to over 8,200 nm				Haggerty, 1994
B-747/400		+ 3%			-4%	Eickmann et al., 2007
B-737/300, /500	-3 to 5%	+ 3%				March, 2007
B-737/700	-2.5 to 5.1 %					Eickmann et al., 2007 & Hine, 2004
B-737/NG	-4 to 5%					APB, 2007
B-757	-5%					APB, 2007
B-727	-5 to 6%	+ 5 to 6%		increased		March, 2007
A300	-1%					FI, 1985
A310	-1 to 5%					FI, 1985
A320	-3 to 4%					Gates, 2008

The evolution of winglets for Airbus Industries continued in recent months. In December 2008, Airbus began a several week-long evaluation to see if APB’s up-sweeping winglets can deliver significant fuel efficiency and performance benefits on their A320 aircraft (Gates, 2008). For this evaluation Airbus and API assumed that the

improved aerodynamics of the two and a half meter high winglets will be able to reduce fuel consumption by 3 to 4 percent, resulting in enhanced performance and a reduction of emissions, both critical factors for airlines and aircraft operators. If the outcome of the analyses provides a positive result, including market and financial aspects, the Blended Winglet™ could possibly be offered by Airbus and APB for the A320-type aircraft.

With the numerous examples of winglet applications on a variety of aircraft, winglets are not compatible or desired for every aircraft. In an unlimited environment, aircraft manufacturers can reduce induced drag by simply increasing the wingspan, which will also result in a reduction in total fuel consumption. However, with larger wingspans, there are generally larger structural loads on the wings that would require increased material capabilities and manufacturing costs. Additionally, the wingspan of aircraft is constrained due to infrastructure limitations and other considerations such as hangar, gate, or taxiway dimensions. While the addition of winglets could provide the same effect as a larger wingspan, this decision would also result in some increased load factors that need to be considered.

When wingspan is not limited, some aircraft may be designed or modified with raked wingtip instead of winglets. While the effects were similar, raked wingtips provide a reduced fuel burn during cruise conditions along with an improved takeoff performance at the expense of longer wingspan. Additionally, raked wingtips offer a takeoff performance advantage over winglets because it improves lift as well as drag, both of which are important for takeoff. With the engineering trade-off for winglets versus raked wingtip extensions being so close, the design space was more favorable for the raked wingtips for the Boeing 777 and 787 aircraft families. By reducing the operating

expenses and limiting any changes to the current infrastructure, commercial operators are able to maximize their investment capital.

Application of Winglets on Military Aircraft

The US military operates numerous aircraft and many of them have commercial variants. When fuel prices began to rise and commercial operators began modifying their aircraft with winglets as a cost saving measure, the USAF and the DoD did not look the other way. The investment in winglets for a particular aircraft type depends on a number of factors, including the potential fuel burn efficiency improvements provided, the size of the statement of work required for the installation, the utilization rate of the aircraft fleet, and the expected lifespan of that particular fleet (Eickmann et al., 2007). Extensive analysis covering engineering and economic aspects would be required for each aircraft type in order to determine the appropriateness of winglet modifications. With these winglet-equipped commercial aircraft, the structure has already been analyzed and determined to be appropriate, the engineering design has been done, the modifications have been prototyped, tested, and certified, modification kits developed, flight manuals revised as required, and so on (Eickmann et al., 2007).

The majority of winglet-equipped aircraft that the US military currently operates are variants of commercial aircraft that also have winglets with the preponderance of those operating as Special Airlift Mission (SAM) aircraft. The C-20A/B is a winglet-equipped military version of the Gulfstream III that was chosen in June 1983 as the replacement aircraft for the C-140B Jetstar. It executes the airlift mission requirements for high-ranking government and Department of Defense officials (AMC/PA, 2006). Another winglet-equipped aircraft is the C-37A based upon the high-altitude

intercontinental Gulfstream V aircraft. Operating in the USAF inventory since 1998, the C-37A is capable of cruise operations from 41,000 to 51,000 feet (AMC/PA, 2008). Identical to the Boeing 737-700 with winglets, the C-40 B/C provides safe, comfortable, and reliable transportation for U.S. leaders to locations around the world since 2000 (AMC/PA, 2008). The C-32 is a specially configured version of the Boeing 757-200 commercial intercontinental airliner. Identical to the Boeing 757-200, the C-32 has different interior furnishings and 21st century avionics (AMC/PA, 2006). Although not originally equipped with winglets, the 2007 National Defense Authorization Act provided funding for the modification to add APB's Blended Winglets™ to the aircraft. The DoD expects to benefit from the same important range benefits, augmented fuel reserves on long-range missions, reduced environmental emissions, and significant cost savings due to dramatically reduced fuel burn, that the airline world now enjoys thanks to Blended Winglet™ technology (Clark, 2006).

The benefits of winglets are not limited to those military aircraft that have commercial variants with modified winglet structures. When the aging C-141s were reaching the end of their service life, the USAF and the DoD were faced with a decision to recapitalize the fleet in order to maintain the readiness required to meet any future needs. In August 1981, the Air Force announced that it had selected the Douglas Aircraft Company Division of McDonnell Douglas to develop the Cargo Experimental (CX) aircraft, now known as the C-17 (Chambers, 2000). This versatile aircraft, which was designed with winglets from inception, has the capability of rapid strategic delivery of troops and all types of cargo to main operating bases or directly to forward bases in the deployment area. Using advanced aerodynamics and an innovative NASA powered-lift

concept, the C-17 combines the outsized load carrying capacity of the C-5 with the short takeoff and landing performance of the C-130 (Chambers, 2000). The C-17 made its maiden flight on Sept. 15, 1991, and the first production model was delivered on June 14, 1993 (AMC/PA, 2008).

Unlike other aircraft in the inventory, strategic or tactical, the C-17 was designed with winglets incorporated for reasons relating to taxi clearance, turning radius, maneuverability, and parking. In particular, the Air Force wanted to limit the wingspan to that of the C-141 to make the C-17 compatible with facility infrastructure. The wingspan limitation was dictated by an Air Force requirement for three aircraft to maneuver on a ramp measuring 90 meters by 122 meters that is connected by a 15-meter-wide taxiway (Chambers, 2000). Clearly the addition of winglets into the design was preferable to achieve the desired climb and cruise performance rather than increasing the wingspan. Other design considerations were debated before the final winglet configuration that is seen today was settled, such as a design with upper and lower winglets. However, due to ground clearance limitations and lower cruise performance, the lower winglet design was eliminated. Additionally, it was determined that the lower winglet would result in higher manufacturing and maintenance costs. Several cooperative wind-tunnel test studies were conducted by McDonnell Douglas and Langley in the National Transonic Facility (NTF) at the Langley Research Center to assess and optimize the cruise aerodynamic performance of the C-17 (Chambers, 2000). As a testament to Dr. Whitcomb's earlier designs, the inclusion of winglets on the C-17 was shown in wind tunnel testing to reduce cruise drag approximately 2.5 percent (Eickmann et al., 2007).

For other aircraft, any wingtip modification would not provide the benefits seen in the aircraft previously discussed or other problems may arise. As an example, the wing of the C-130 is already very efficient because of the design's high aspect ratio. Because of the unswept wing design, there is a lower wingtip load factor. This is counter to the conditions where winglets provide the greatest benefit; that is, aircraft used for longer ranges and higher altitudes along with the higher wingtip load factors. Another example is the C-21 operational support aircraft. These aircraft, based on the commercial Learjet 35A business jet, are equipped with wingtip fuel tanks. Any wingtip modifications would require these tanks to be removed, which would severely limit the range of these aircraft. Additionally, due to the amount of fuel that these aircraft use, the payback period would extend far beyond the life expectancy of this aircraft.

Winglets and the KC-135

The KC-135 Stratotanker has provided the core aerial refueling capability for the United States Air Force and has excelled in this role for more than 50 years (AMC/PA, 2008). Based on Boeing's model 367-80, the KC-135 shared its basic design with the commercial 707 passenger plane. The Air Force purchased the first KC-135 aircraft in 1954. The first delivery was in June 1957 and the last delivery was in 1965 (AMC/PA, 2008). Of the total 820 KC-135 aircraft built: 732 were built as aerial tankers and 88 were modified for special purposes including cargo carriers, reconnaissance airplanes, Strategic Air Command Airborne Command Posts, and transports for high-ranking government officials (Boeing, 2007). As an aerial tanker, it offloads an average of 19 million pounds of fuel in any given month to US military and coalition aircraft allowing pilots to complete their missions (Boeing, 2007).

With its rich history and unparalleled performance, the KC-135 is no stranger to winglets. The positive conclusions of the DC-10 wind tunnel test and the Boeing 747 engineering study completed in the late 1970s, coupled with Dr. Whitcomb's work, prompted the Air Force to consider the possible installation of winglets on the KC-135 aircraft (NASA, 2004). Although other aircraft were considered, the KC-135 was chosen as the test platform because it featured an elliptical-type span loading with relatively high loads on the outer wing panels similar to other early commercial transport aircraft (Chambers, 2003). The goal of the joint \$3.1 million project between NASA and the USAF was to reduce cruising drag by about 8 percent. Moreover, it was proposed that, if the tests were successful, such a modification to the entire KC-135 fleet could save more than 45 million gallons of fuel based on 1975 aircraft utilization rates (FI, 1977).

The aerodynamic winglet design for the KC-135 was completed by Dr. Whitcomb and his staff at Langley while the Boeing Wichita Division accomplished the structural design and fabrication. As mentioned earlier in this chapter, the wind tunnel and flight test results were impressive: a 7 percent gain in the lift-drag ratio and a 20 percent reduction in drag due to lift were achieved at the cruise condition (Chambers, 2003) (see Figure 12). If retrofitted to the KC-135 fleet, more than a billion dollars worth of fuel could be saved over the next 20 years (Montoya, 1980). Despite the impressive possible benefits shown by these early evaluations, the combination of Air Force priorities and limited budget options resulted in a decision to retrofit the KC-135 fleet with new engines, rather than winglets, as a more efficient fleet modification.

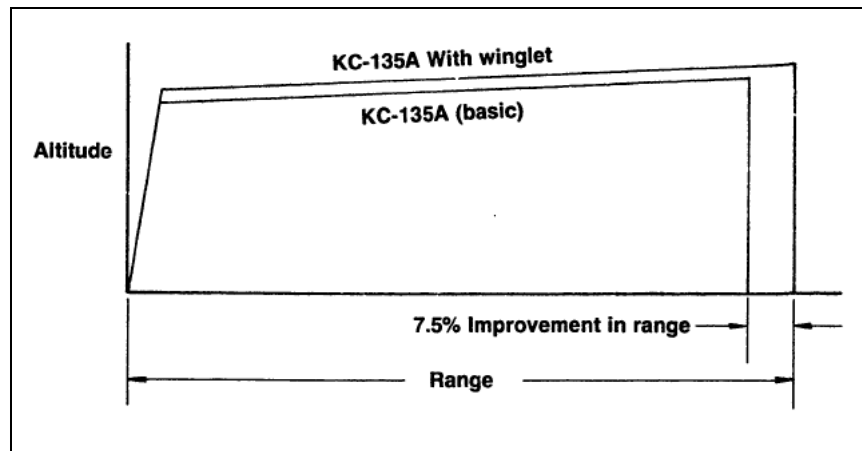


Figure 12: Effect of Winglets on Range Performance (Loptien, 1976)

In recent years, there has been a renewed interest in winglet modifications for the KC-135 fleet. In an effort to increase fuel efficiency, several Congressional directives were included in the NDAA for FY2007 and FY2009 to analyze the effectiveness and the engineering feasibility of winglets for military aircraft. In response to the FY2007 directive, the National Research Council (NRC) found in its study that wingtip modifications offer significant potential for improved fuel economy in certain Air Force aircraft, particularly the KC-135R/T and the KC-10 (Eickmann et al., 2007). To address the FY2009 directive, the RAND Corporation has been contracted to perform a winglet study that will address three main issues: 1) the investment costs required to add winglets to the KC-135 and KC-10 tankers, 2) the operational cost savings resulting from adding the winglets, and 3) whether the initial investment will be recovered over the remaining useful life of the KC-135 and the KC-10 tanker fleet (Croft and Stevens, 2008). The results of this study are not expected until May 2009. Other academic studies have addressed the issue of winglet modification on the KC-135 in some fashion, including the USAFA Department of Aeronautics, Air War College, Air Command and Staff College, and Marine Corps Command and Staff College. Despite the majority of

these studies in favor of winglet modifications, there are many issues that were not addressed. Limited budgets, quantum leaps in future technology, age and utilization of the current fleet all play an important role in the cost effectiveness of the proposed concept. Only history will tell if the findings of these studies were accurate or not.

III. Methodology

For too long our nation has been dependent on foreign oil. And this dependence leaves us more vulnerable to hostile regimes and to terrorists – who could cause huge disruptions of oil shipments, raise the price of oil and do great harm to our economy. ... It is in our vital interest to diversity America's energy supply – and the way forward is through technology.

-- President George W. Bush
State of the Union Address
January 23, 2007

This chapter explains the methods used to answer the two research questions proposed in Chapter 1. This research investigated a set of KC-135R missions, the cost of JP-8 jet fuel, and performed a cost-benefit analysis to determine if winglet modification would be cost effective within the remaining life-cycle of the KC-135R aircraft.

Data Sources

In order to outline the possible application and cost benefits of winglets, this research focused on the missions flown by McConnell Air Force Base during the fourth quarter of FY2008--July through September. As the largest of the three active duty supertanker KC-135 wings, McConnell AFB executes the full spectrum of KC-135R missions including air refueling, local training, formal navigator training, receiver air refueling, and special operations air refueling. As the leader in both the number and type of KC-135R missions flown, it was determined that McConnell AFB provided a representative cross section of KC-135R sorties flown throughout the Air Force.

With the location and time frame determined, a history report was retrieved from Global Decision Support System 2, or GDSS-2. The data sample of sorties included local air refueling training missions, pattern-only training sorties, operational air refueling

missions, and cargo missions. This information was synthesized with the fuel data report obtained from the 22d Operations Group/Standardization and Evaluations (22 OG/OGV).

To give a historical perspective on DoD fuel expenditures, the contracted fuel rates were obtained from the Defense Energy Support Center (DESC) dating back to FY1996. Although these rates were normally contracted for the entire fiscal year, with the volatility of crude oil prices in the recent past, the contracts were renegotiated once or twice. The reports were utilized in analyzing past fuel expenditures as well as in the regression analysis to estimate future fuel costs. The data collected on fuel cost was also adjusted for inflation to 2009 dollars using the consumer price index inflation calculator found on the Bureau of Labor Statistics website.

Table 2: Sample of GDSS-2 History Report for McConnell AFB, KS

Mission ID	Call Sign	Msn Type	Est Dep Time	Act Dep Time	Est Arr Time	Act Arr Time	Est Flying Time	Flying Time
8MY400H26184	Reach 954	Contingency	3 Jul 08 1030	3 Jul 08 1030	3 Jul 08 2100	3 Jul 08 2100	10+30	10+30
8VC405200188	Reach 1299	Channel	4 Jul 08 0031	3 Jul 08 2316	4 Jul 08 0128	4 Jul 08 0151	0+57	2+35
8VH355L1S183	Ruby 35	AR	4 Jul 08 0645	4 Jul 08 0558	4 Jul 08 0728	4 Jul 08 0727	0+43	1+29
8VH355L1S183	Ruby 35	AR	4 Jul 08 0700	3 Jul 08 2157	4 Jul 08 0345	4 Jul 08 0345	12+00	5+48
8JM110801188	Reach 1108	SAAM	6 Jul 08 2330	6 Jul 08 2323	7 Jul 08 0224	7 Jul 08 0223	2+54	3+00

Data Format

The quantitative data used to address the research question was exported to Microsoft Excel 2007[®] from Global Decision Support System-2 (GDSS-2), information systems that enable HQ AMC to command and control its assets. Although there are multiple options available that allow users to customize the report, the GDSS-2 history report obtained for this research contained only the critical mission details including mission identification and type, call sign, planned and actual departure times, planned

and actual land times, and planned and actual flying time. Table 2 lists the first few sorties included in the data set.

As a monthly requirement to HQ AMC, a fuel data report is compiled from the AF Forms 79, Aerial Tanker In-Flight Issue Logs as well as the unit Tanker Activity Reports. These reports are used for fuel performance tracking of all the command's aircraft. The fuel data report added the following information to the history report: planned and actual ramp fuel, planned and actual fuel off-load and fuel on-load, planned and actual fuel shutdown, as well as actual fuel burn rates with comments for any deviations. The first few sorties included in the data set are shown in Table 3. The summary of the data set, a synthesis of the information from the GDSS-2 History Report, and the McConnell AFB Fuel Data submitted to HQ AMC, is discussed later in Chapter 4, as well as supplemental information shown in Appendix A.

Fuel Use and Cost: Past, Present and Future

Prior to performing any analysis on the data, this research focused on another aspect that is critical to the potential benefits of winglet modification—fuel use and costs. As the US government's largest fuel user, the DoD accounts for 93 percent of overall federal energy costs; however, the Pentagon totals only about 2 percent of the nation's entire energy use even with such a huge fuel bill (Schanz, 2007). Approximately 74 percent of the DoD's energy use powers its mobility vehicles—Air Force aircraft, Navy ships, and Army ground vehicles—and roughly 52 percent of the total is comprised of aviation fuel (see Figure 13). Putting that into perspective, both military and civilian aviation accounts for only 4 percent of energy use in the United States (MITRE Corp, 2006).

Table 3: Sample of McConnell AFB Fuel Data Report Submitted to HQ AMC

Date		Call Sign		(TANKER ONLY)				(RECEIVER ONLY)				BURN RATES				Remarks
				RAMP FUEL		FUEL OFFLOAD		FUEL ONLOAD		SHUTDOWN FUEL		DURATION		Burn Rates		
				Planned (1000 lbs.)	Actual (1000 lbs.)	Planned (1000 lbs.)	Actual (1000 lbs.)	Planned (1000 lbs.)	Actual (1000 lbs.)	Planned (1000 lbs.)	Actual (1000 lbs.)	Planned (Hours)	Actual (Hours)			
1 Jul 08		Turbo 71		110	109.9	10	10	0	0	45	46.9	5.0	4.9	10.8	ERRC to Turbo 20	
1 Jul 08		Turbo 72		75	75.3	10	8	0	0	17	20.6	5.0	4.7	9.9	Rcvr took less than frag	
1 Jul 08		Turbo 03		75	77	30	30	0	0	18	20.1	0.0	2.5	10.0		
1 Jul 08		Turbo 20		45	44.9	0	0	0	0	20	14.5	3.0	3.2	9.5		
1 Jul 08		RCH 299		111.4	124.7	0	0	0	0	8.8	22.2	9.0	9.2	11.1	IMF planned to land w/ 8.8k.	
1 Jul 08		Turbo 27		65	65.4	0	0	0	0	18	32	4.7	2.5	13.4	Rcvr CANX after engine start.	
1 Jul 08		Turbo 28		80	78.6	0	0	0	0	20	40.6	6.0	3.1	12.3	High fuel burn D2 grd time	
2 Jul 08		Turbo 71		55	54.2	10	10	0	0	15	16.4	2.7	3.0	9.3		
2 Jul 08		Turbo 72		83.7	83.7	10	10	0	0	36	36.7	2.4	3.4	10.8	ERRC to Turbo 33	
2 Jul 08		Turbo 30		140	140.2	10	0	0	0	19	34.8	9.7	7.9	13.3	Late T/O. AR CANX	
2 Jul 08		Total 33		55	36	0	0	0	0	20	14	3.0	2.3	9.6		
2 Jul 08		Woodh 22		140	139.4	64	0	34	0	15	66	6.1	3.2	10.6	RTB early D2 Rcvr CANX	
2 Jul 08		Turbo 81		80	79.1	10	10.6	0	0	23	21.8	5.0	5.0	9.3	Planned by SOAR Shop	
2 Jul 08		Turbo 74		62	140	0	0	25	25	15	41.7	6.0	4.2	12.0	Late T/O D2 weather.	

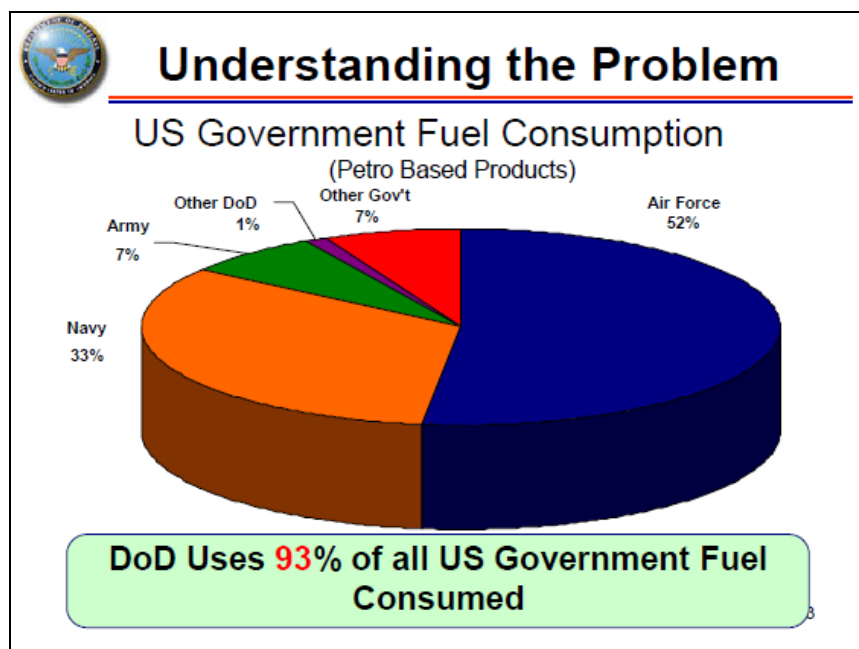


Figure 13: US Government Fuel Consumption
(via Mr. DiPetto, 2006 PEO/SYSCOM Commanders' Conference Briefing)

Although the cost of energy has been increasing steadily for the last century, the recent volatility in oil prices has made energy conservation and budget planning an emphasis item with individuals and senior leaders alike. Fuel expenditures have a significant impact on the department's operating costs even though the costs are only about 2 percent of the total DoD budget. This is especially true for the Air Force. As shown in Figure 14, aviation fuels accounted for 89 percent of all Air Force fuel, totaling approximately 2.7 billion gallons in FY2005. Of this total, non-fighter aircraft accounted for approximately 64 percent of Air Force aviation fuels or approximately 1.7 billion gallons (DESC, 2005). Since the Air Force operates most of DoD's fixed-wing aircraft, it spends the largest share of the department's fuel budget. For every \$10 increase in the price of a barrel of oil, the operating costs of the Air Force increase by approximately \$650 million. Because the DoD budgets for fuel a year in advance, the cost increases must be paid for with emergency funds or by shifting funds from other programs.

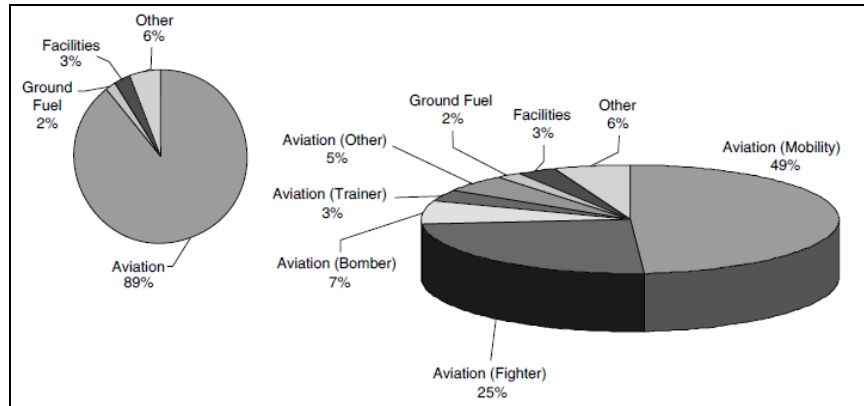


Figure 14: Distribution of Air Force Fuel Usage (via DESC)

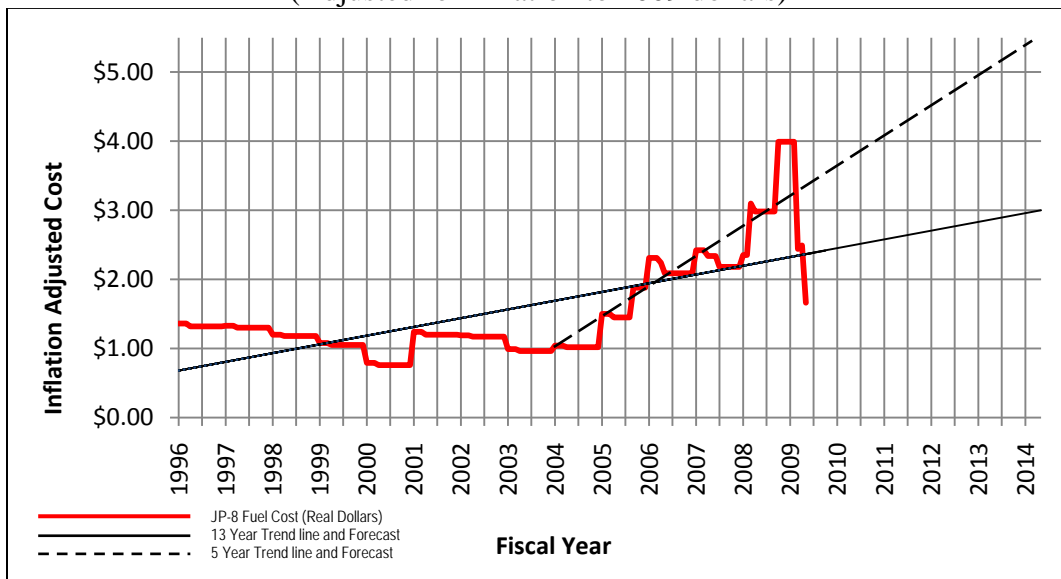
The purchasing and distribution of petroleum products, including JP-8, is the responsibility of the Defense Energy Support Center (DESC) whose mission is to provide the Department of Defense and other government agencies with comprehensive energy solutions in the most effective and economical manner possible. The recent volatility in crude oil prices has made the DESC mission difficult. The DoD's bill for jet fuel in FY2000 was \$2.2 billion, while the FY2006 total was \$7.9 billion which represents a 73 percent increase after adjusting for inflation (Lengyel, 2007). With the elevated operations tempo during this time largely attributable to the Global War on Terror, this increase only accounts for 12 percent of the total gallons consumed. Therefore, the majority of the increased costs can be attributed to the price of jet fuel.

In recent years, DESC has had to adjust the contract price for JP-8 multiple times during the year. Whereas historically the prices were set for the entire year, these recent efforts have been an attempt to maintain some relationship between the contracted price for JP-8 and the actual price of crude oil. Table 4 below depicts the historical prices that DESC contracted for JP-8 since FY1996, adjusted for inflation to 2009 dollars. During the time frame on the table, the price of JP-8 increased 299 percent from FY2000 to

FY2008. Increases of this magnitude make it extremely difficult to minimize operational costs during periods of elevated operational tempos.

To get a thorough understanding of the historical fuel cost and the potential future increases, a trend analysis was accomplished using Microsoft Excel 2007[®]. To begin the analysis, the DESC contracted fuel prices obtained from the DESC website are listed as monthly amounts on the spreadsheet. The annual contract rates for bulk fuels dating back to FY1996 were available on the website and used in the analysis. Then these amounts were adjusted to 2009 dollar values using the inflation calculator available on the Department of Labor website. To estimate the future fuel expenditures, the linear regression equation was determined from the historical data using the least squares best fit method. Several regression lines were calculated to account for long-term consistent minute changes, as well as the larger volatile changes in recent years. Therefore a 13 year history was used to develop one trend line, while 5 year history was used to develop a second trend line.

Table 4: DESC Contracted JP-8 Fuel Cost
(Adjusted for inflation to 2009 dollars)



By applying trend analysis to the DESC contracted fuel prices, the graph in Table 4 depicts the trend line with a five year forecast. Using the last 13 years, DESC could expect an increase in the cost of JP-8 to about \$3.05 by the beginning of FY2014 based on 2009 dollars. This forecast was computed using the regression formula $y = 0.0105x + 0.6678$ (with monthly periods) and is the worst-case scenario in the cost analysis. In this equation, x represents months and equals 227 months for the FY2014 forecast. While this may be counterintuitive, from a modification cost perspective, this scenario is the worst-case because the lower the fuel prices, more time is required to recoup the cost of the modification. With the majority of the fuel price increases occurring since the beginning of FY2005, the forecast price from this historical set is quite different. This alternate forecast would be near \$5.35 at the beginning of FY2014 based in 2009 dollars using the regression formula $y = 0.0371x + 0.8847$, again using monthly periods where x equals 120 for the FY2014 forecast. This forecast will also be used in the cost analysis as the best-case scenario, again because the higher fuel prices result in a small time period to recoup the cost of the modification. This research determined that the most-likely case scenario is a forecast that predicts fuel cost to be somewhere between the two values, around \$4.20 per gallon of JP-8 by FY2014.

Cost-Benefit Analysis

A cost-benefit analysis is a technique designed to determine the feasibility of a project or plan by quantifying its costs and benefits. Traditionally, cost-benefit analysis considers three viable alternatives; however this research only analyzed two alternatives: modify the KC-135R with winglets or retain the aircraft in its current configuration. With these two alternatives, the analysis considered fuel costs as determined in the

previous section, the cost of modifying the aircraft, the potential savings achieved from a winglet modified aircraft, as well as the life expectancy of the aircraft.

Table 5: Commercial Transport Aircraft Winglet System List Prices
(Via APB website)

Blended Winglets – System List Prices	
Aircraft	Base Price Uninstalled
737-700/800/900	\$885,000
737-300/500	\$650,000
757-200	\$935,000
757-300	\$1,000,000
767-300ER/F	\$2,110,000

Because there is not a developed winglet modification kit for the KC-135R, the cost of modifying the aircraft was determined by best estimates based on historical information from the NASA KC-135A test during the late 1970s and current winglet modification prices on similar sized aircraft. These winglet studies concluded that the winglet modification of the KC-135A with the AFFDL/Boeing winglets would cost an estimated \$66,000 per unit based in 1977 dollars. Adjusted for inflation, that estimate would be about \$230,000 in 2009. Personnel at the Business Development office at the Boeing Company, Integrated Defense Systems quote a price of \$1M for their version of a winglet modification. Likewise, Table 5 details the cost estimates for APB’s Blended Winglet™ modification of commercial transport aircraft comparable in size to the KC-135R. According to the APB website, these cost estimates include the Blended Winglets™, wing modification kit; all other necessary materials, parts and fasteners; data; software; manuals and technical documentation; proprietary installation tooling, installation job cards/planning, as well as on-site installation technical support. With these values in mind, the cost-benefit analysis developed two options with different

prices for the KC-135R winglet modification: Option A uses \$1M for the cost while Option B assumes \$1.5M for the cost, both based in 2009 dollars.

Throughout Chapter 2, the various benefits achieved from winglets on multiple aircraft were discussed, including fuel savings. The fuel savings ranged from 1 to 3 percent on A310, A320, and B-747 aircraft to 4 to 6 percent on the B-727, B-737 and B-757 aircraft as summarized in Table 1 on page 26. The winglet studies on the KC-135A that NASA completed during the 1970s and 1980s exhibited similar savings. Although Dr. Whitcomb's test concluded a fuel savings of over 6 percent on the winglet equipped KC-135A, this research was more conservative in its fuel saving estimates. For the McConnell AFB sortie data set, an average fuel savings rate of 4 percent was applied through the use of a random number generator. This percent savings was normally distributed with a standard deviation of 0.75. As an assumption, it was determined that this method accounted for the variations of individual pilot techniques used during the sorties as well as the variations in the types of sorties flown.

The final aspect considered in the winglet modification analysis was the life expectancy of the KC-135R. As with some long-term investment program, the KC-135R winglet modification program requires a large initial investment in which small consistent returns are expected over time. In order to recover the initial investment, the aircraft needs to be utilized for many years so the accumulated annual savings would eclipse the modification costs. Unfortunately, the life expectancy of the KC-135R is contingent upon the addition of the next generation tanker, KC-X. With delays in the acquisition of the KC-X during recent years, the requirement to operate the KC-135 is prolonged. As reported in the 2004 Defense Science Board Task Force Report on Aerial

Refueling Requirements, the average KC-135R airframe had flown only about 17,000 hours of an estimated service life of 39,000 hours. Thus, the task force concluded that KC-135R airframes were viable until the year 2040 (Pilling, 2004). With the acquisition of the KC-X in the solicitation phase, this analysis utilized the task force’s assumption that the KC-135R will remain in service beyond the year 2040, with a plan to begin retirement of the aircraft beginning in FY2018 as depicted in Figure 15.

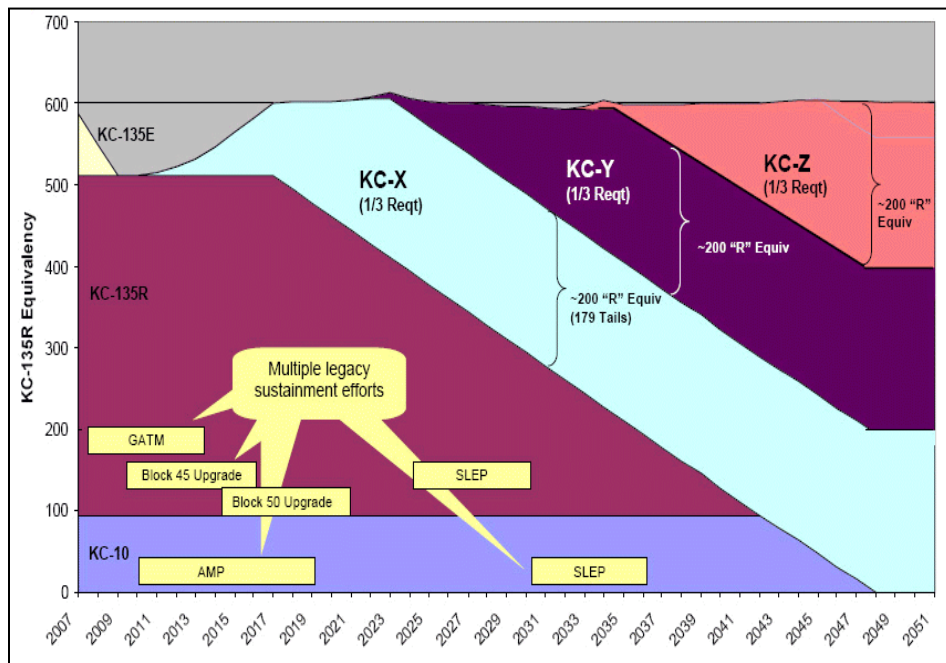


Figure 15: The 40-Year Tanker Recapitalization Plan (AFA, 2008)

In addition to the assumptions already discussed, there were other assumptions that were included in the cost-benefit analysis. Because the value of money changes over time with changes in the inflation rate, this was also accounted for in this research. A flat rate of 3.5 percent, the historical annual average rate since 1914, was applied to all future monetary amounts including the winglet modification prices and the rising fuel costs. Similar to the life expectancy of the aircraft, the number of hours flown was another assumption. In discussions with HQ AMC/A4, they reported that the average flying rate

for the KC-135R in recent years has been nearly 735 hours per year. Due to increased operations tempo in conjunction with the Global War on Terror, this rate was assumed until the year 2015, at which time the annual rate per aircraft would be reduced to the planned rate of 425 hours per year. Finally, the total number of aircraft modified and the annual number of aircraft modified were other assumptions included in the analysis. Due to retiring aircraft and limited “payback” availability, only 200 of the current 417 aircraft were modified in the analysis. Additionally, the modified aircraft were completed at a rate of 20 per year. As an example, the first 20 aircraft were modified in 2010 with the fuel savings beginning in 2011. This process continued until all aircraft modifications were completed in 2019.

The results of the cost-benefit analysis and implications are discussed in Chapter 4, Results.

IV. Results

To assist in our efforts to communicate our energy strategy, every Airman should develop new ways to personally and organizationally conserve energy. Your efforts in making energy conservation a part of your day-to-day activities will benefit our entire Air Force, and free up precious dollars for other critical programs.

-- Michael W. Wynne
Secretary of the Air Force
Letter to Airmen
September 6, 2006

Results of Analysis

This chapter details the results of the research. Based on the cost-benefit analysis, along with the included assumptions of the analysis, this research proposed a plan to modify a limited number of KC-135R aircraft with winglets over a ten year period at a rate of 20 aircraft per year. With the modified aircraft in the inventory, this analysis provided the estimated fuel savings in terms of a dollar amount that is possible through the remaining life cycle of the aircraft. Central to this analysis are the two research questions proposed in Chapter 1.

Question 1, Winglet to Increase Efficiency

Are winglets a valid way of decreasing the fuel burn rate, thus increasing the aircraft range and endurance (or efficiency) of the KC-135R?

The data set from McConnell AFB included 349 sorties that were completed during the study period, July 2008 through September 2008. These sorties totaled 1,285.3 flight hours and averaged 3.7 hours per sortie. When analyzing the fuel burn rates, the average rate for these sorties were 10,248 lbs/sortie, or a total of 3,576,770

pounds of JP-8 used during the quarter, as shown in the left column of Table 6 below. Using the DESC fuel rate of \$1.66 per/gallon (current as of February 1, 2009), that equated to a total fuel operating expense of \$886,184 (note 1 gallon = 6.7 pounds of fuel).

However, when executing the same sorties with winglet equipped aircraft, lower fuel burn rates would be realized. Utilizing the normally distributed fuel burn rate detailed earlier, the analysis provided a range between 1.8 and 6 percent, with the mean of 4 percent. With this method of analysis, the fuel burn rate decreased to 9,840 lbs/hour, or a total of 3,434,225 pounds of JP-8, as shown in the right column of Table 6 below. In other terms, these missions could have provided the receivers with an additional 1,500 pounds of JP-8, remained airborne for an additional 15 minutes if needed, or flown an additional 105 nm without using more jet fuel than the non-winglet equipped aircraft. This reduced fuel burn rate equated to a fuel savings of \$35,317.05 for the quarter or \$141,268.20 for the year when paying \$1.66 per/gallon.

Table 6: Descriptive Statistics on Reported and Potential Fuel Burn Rates (in 1,000s)

Reported Fuel Burn Rate		Potential Fuel Burn Rate	
Mean	10.25	Mean	9.84
Standard Error	0.0613	Standard Error	0.0584
Median	10.2	Median	9.831
Mode	10.9	Mode	N/A
Standard Deviation	1.146	Standard Deviation	1.092
Sample Variance	1.313	Sample Variance	1.192
Kurtosis	13.329	Kurtosis	12.037
Skewness	1.323	Skewness	1.157
Range	15.2	Range	14.3
Minimum	4	Minimum	3.820
Maximum	19.2	Maximum	18.09
Sum	3576.77	Sum	3434.23
Count	349	Count	349
Largest (1)	19.2	Largest (1)	18.09
Smallest (1)	4	Smallest (1)	3.82
Confidence Level (95.0%)	0.121	Confidence Level (95.0%)	0.115

Question 2, Cost Effectiveness

Is modifying the KC-135R with winglets a cost-effective method of reducing the operating cost for the aircraft and the USAF?

To determine the cost effectiveness, this research analyzed the initial expenditures and the outcomes of future years, or cost of the winglet modification and savings potential obtained from the modified aircraft. With cost effectiveness of the winglet modification, the existing service of air refueling was not altered from the perspective of the customer, or the receiver. This analysis determined the fuel savings in terms of dollar values for each year remaining in the life cycle of the aircraft. Adjusting for inflation, an average break-even point was determined for each individual annual purchase, as well as the overall modification purchase. Stated a different way, the purchase break-even point was the amount of years required to recoup the cost of modifying one years' purchase of 20 modified aircraft. The overall modification purchase break-even point was the number of years required to recoup the costs for the entire modification program of 200 aircraft. These values were determined for both scenario options: Option A (\$1.0 million cost per winglet modification) and Option B (\$1.5 million cost per winglet modification).

As Table 7 depicts, the average annual break-even point for Option A of the Best-Case Scenario was 5.2 years while the break-even point for Option B was 7.6 years. In the Most Likely Case Scenario, the break-even points were 7.1 years and 10.3 years for Options A and B, respectively.

Table 7: Average Break-Even Point for Each Year’s Modification

PURCHASE BREAK EVEN POINTS (in years)		
	Option A (\$1.0M)	Option B (\$1.5M)
Best Case Scenario	5.2	7.6
Worst Case Scenario	11.2	15.9
Most Likely Case Scenario	7.1	10.3

With additional aircraft modified, the amount of annual savings increased as the total number of hours flown with lower fuel burn rates increased. This can be seen when the overall break-even point was compared to the individual break-even point of the modification of the last planned purchase in 2019. Looking at Option A of the Best Case Scenario, the overall break-even point was just 10.0 years after the initial purchase, as shown in Table 8 below. When comparing that to the individual break-even point of the 2019 purchase, the last purchase achieved positive savings over five years after the modification, sometime in 2025. However, with the saving from the previous years’ modifications, the savings achieved from all modifications surpassed the investment cost over four years earlier in 2021.

Table 8: Average Break-Even Point of All Modifications

OVERALL BREAK EVEN POINTS (in years)		
	Option A (\$1.0M)	Option B (\$1.5M)
Best Case Scenario	10.0	12.5
Worst Case Scenario	15.8	20.6
Most Likely Case Scenario	11.9	15.0

The earlier overall break-even point was observed for both options of all three scenarios; however, there is another aspect that is important to note here. Even with the latest overall break-even point, Option B of the Worst Case Scenario, the observed 20.6 years was well within the expected life cycle of the KC-135R. In this scenario, the fuel

savings surpassed the modification cost during the year 2030, which would yield over ten years of additional savings. With annual savings exceeding \$65 million at the highest point, that option totaled a life-cycle savings of over \$176 million. The level of savings was much higher for the other scenarios.

From a different point of view, analyzing the three scenarios of Option A provided a clear picture of the amount of savings potential with each scenario. Figure 16 below illustrates the variation of the three curves which picture the annual savings for the three scenarios over time, especially when comparing number of years below and above the \$0 line. For all three curves, the amount declined from 2010 to 2019 as these were the years of the winglet modification investment. From 2020 through 2032, the curves moved to a positive trend as all 200 aircraft were modified and achieved the expected fuel savings. In 2033, the first of the modified aircraft would begin to retire at a rate between 16 or 17 aircraft per year thus affecting the total amount of fuel savings possible. This reduced savings trend would continue until 2042 when the last winglet modified KC-135R would be retired.

When analyzing Option B, the curves of all three scenarios are similar to that of Option A, just shifted to cover the additional investment cost of modifying each aircraft. With all variables being equal to Option A, other than the modification cost, the total amount of annual savings for each curve would be slightly lower than those of Option A, as seen in Figure 17. As to be expected, the amount of time required to break even would also be longer, which would affect the total savings achieved. However, all three curves show positive savings through the life cycle of the modified aircraft.

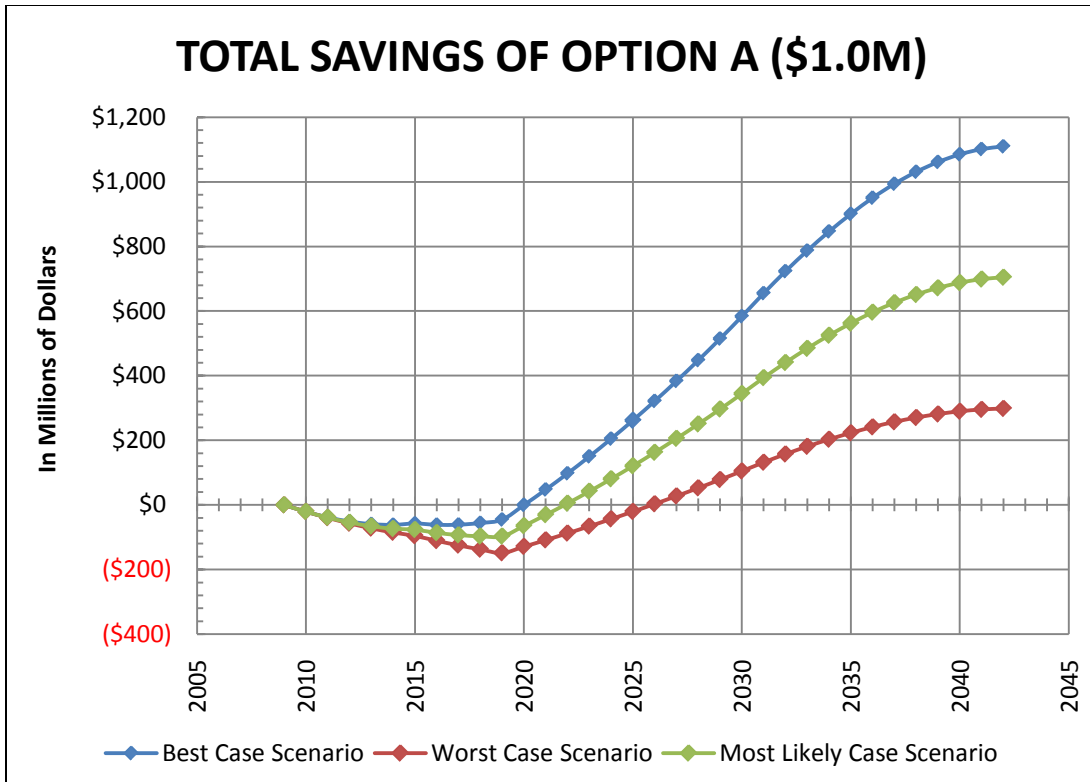


Figure 16: Potential Total Savings under Option A

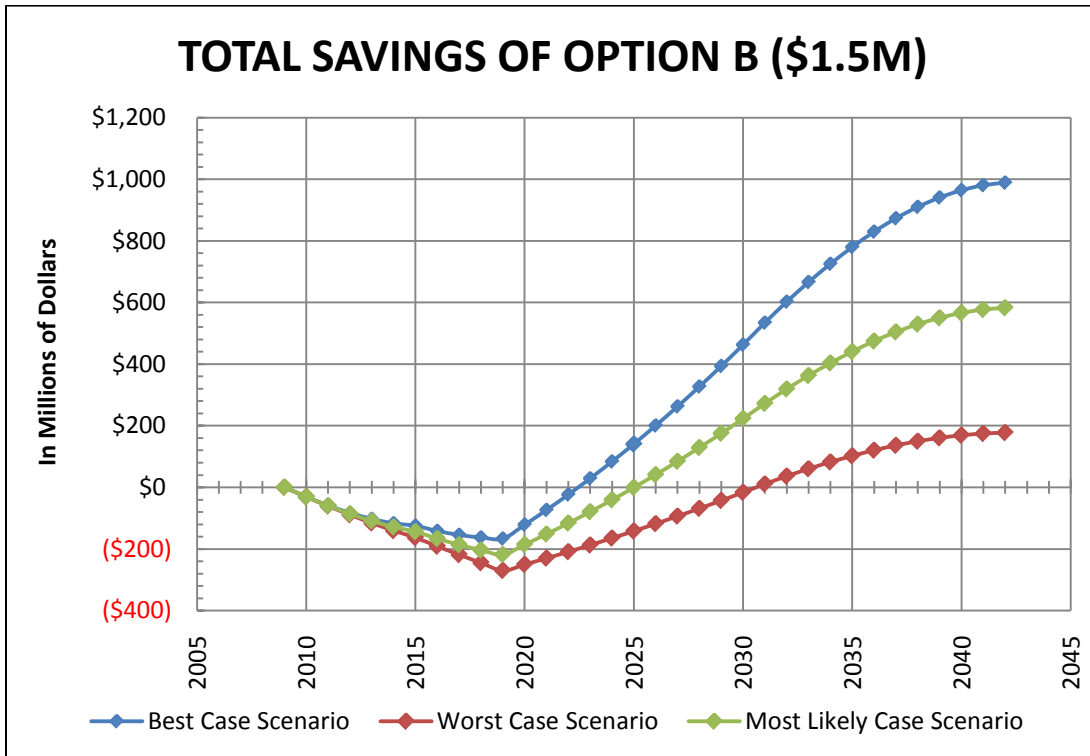


Figure 17: Potential Total Savings under Option B

Implications

With the overall break even points for both options of the three scenarios well within the expected life cycle of the KC-135R aircraft, it is implied that the winglet modification would be cost effective. This analysis quantified the effectiveness of the modification to a dollar value which senior leaders can use in making their decision on future winglet programs. With the three scenarios, the potential savings of the winglet modification ranged from over \$1.1 billion seen in the best case scenario to just over \$177 million found in the worst case scenario. Focusing on the most likely case scenario options, the potential savings obtained from the modification ranged from over \$703 million for Option A to over \$582 million for Option B, as depicted by the green line of Figures 16 and 17. That is a potential savings of 289 percent above the \$242 million invested and a savings of 159 percent above the \$364 million invested for Options A and B, respectively. Considering these are estimates based on stated assumptions, any additional operating years beyond 2042 would increase the savings obtained.

V. Discussion

The important thing is not to stop questioning. Curiosity has its own reason for existing. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity (Adair, 2007).

-- Albert Einstein
American Physicist
1879 – 1955

The final chapter concludes this research by discussing second-order effects of the winglet modifications, alternative energy and fuel conservation strategies, as well as suggestions for potential future research efforts.

Second-Order Effects

As detailed in the previous chapters, investing in a winglet modification provides a significant fuel savings over the life cycle of the aircraft. Aside from the additional benefits summarized in Table 1, winglets provide other positive improvements not accounted for in the cost analysis. In addition to a lower fuel burn rate, other benefits of a winglet modified KC-135R include reduced engine wear, increased take-off weight, improved climb performance, increased on-station time and fuel offload capability, increased range, as well as decreased engine noise and emissions (Godby, 2008). While these benefits are interpolated from other aircraft, those directly affecting the receiver aircraft are intriguing. With the decreased and displaced wake turbulence as a result of winglets, the net effects should be a more stable airspace for the receiver to refuel. Additionally, with the lower fuel burn rate and increased offload capability, it is possible that fewer assets would be needed to meet operational requirements.

However, there are other ramifications that should be accounted for prior to committing to any large modification program. Aside from the cost of the modification that was detailed in the cost analysis, there are potentially other costs that may be impacted with a winglet-equipped KC-135R. By increasing the wingspan, there may be an impact on airfield ground operations such as parking, taxiing, and maneuvering the aircraft. Certain structures may be an issue during ground operations with the increased winglet height that damage both the aircraft and the obstacle. The added wingspan along with a vertical surface at the wingtips may necessitate modifications to current aircraft hangars. Some hangars may be required to be rebuilt altogether. These requirements could quickly dwarf the potential fuel savings achieved with the winglet modification. The potential added costs were outside the scope of the cost analysis performed in this research, but should be thoroughly researched before the investment decision is made.

The second order effects could potentially affect flight operations as well. Winglet modifications might interfere with antennas, sensors, or critical aircraft equipment on the KC-135R aircraft such as the aircraft lighting systems, the anti-icing systems, and lightning strike dissipation systems. The added vertical surface could potentially lower the cross-wind limitations for aircraft departures and arrivals. With a smaller operating window, the support to receiver aircraft could become more limited in marginal weather conditions. These issues should be thoroughly assessed before committing to any winglet modification investment.

Alternative Fuel Conservation Initiatives

While winglets are a viable fuel saving measure, there are other options available that the DoD could utilize to lower fuel cost. One option that could improve the fuel

utilization is upgrading the KC-135R mission computer with the capabilities found in the C-17. Although recent changes in the operational procedures terminated the practice of standard fuel loads, the sorties flown still ferry additional fuel not required for mission accomplishment. By upgrading the mission computer with the capabilities of the C-17, crew members could precisely calculate their fuel usage data for and during the entire flight to include missed approaches, holding and divert fuel data. Other user entries available to C-17 crews include fuel usage for auxiliary power units, off-course maneuvering, and anti-ice use in flight as well. The data available with a software upgrade would alleviate the use of the current rules of thumb and give crew members the precise data to prevent the extra fuel ferry cost.

A second option that addresses the fuel cost of the KC-135R mission is improving the current scheduling procedures in order to take advantage of proximity between tankers and receivers. Although several methods are available, one process that could be implemented is dividing the continental United States into regions. The requested air refueling would be accomplished by tanker aircraft in the region using any available asset; guard, reserve or active duty aircraft and aircrews. While this is being accomplished to a certain extent at the Tanker Airlift Control Center at Scott AFB, IL, there are definite improvements that could be made in this regard.

A final option to address fuel usage is to expand the utilization of synthetic fuels and biofuel technology. Synthetic fuel is any liquid fuel obtained from non-renewable coal, natural gas, or biomass. Biofuels are solid, liquid or gaseous fuels derived from relatively recently dead biological material such as corn, sugar cane, and prairie grasses.

While these will not reduce the amount of fuel required for aircraft to operate, they do offer options to the limited fossil fuel resources on which the DoD is currently dependant.

Areas for Further Study

The focus of this research was to analyze the effectiveness of modifying the KC-135R in order to lower the fuel expenditures. While this study found that the fuel savings exceeds the modification cost and briefly discussed some second-order effects, there are several areas that warrant future studies which were beyond the scope of this research. Similar to the Mobility Capabilities and Requirements Study and the Mobility Requirements Study, an in depth look at tanker requirements is needed. Included in this study should be a detailed life cycle cost analysis of the KC-135R. Similar to the KC-135R life cycle, a thorough study should be completed that analyzes the repercussions of any delay of KC-X acquisition. Although the decision has not been made at this time, the possibility exists that the purchase may be delayed by an additional 5 years which is certain to affect the current tanker fleet. Finally, although the modification is fiscally sound, the fuel savings are based on assumptions and anecdotal evidence of other aircraft. In order to get a more definitive understanding of the benefits and negative effects of winglets, further model simulations are required. The simulator findings should also be reinforced with an updated prototype in which actual flight tests could be accomplished. With an updated test model available, further insight could be gained on areas such as wake turbulence effects on receivers in addition to the fuel benefits.

Conclusion

The goal of this research was to confirm the usefulness and cost effectiveness of modifying the KC-135R with winglets. Through numerous examples within the

commercial aviation industry as well as other military aircraft, winglets have been shown to provide various benefits with an emphasis on reduced fuel usage. It was demonstrated that the KC-135R is a possible airframe that would benefit from the winglet modification, which could result in millions in fuel savings alone. These potential savings from reduced fuel use could be used for other requirements. At this point, the issue is left to decision makers on how they will utilize the limited funds that may be available.

Appendix A McConnell AFB KS Sortie Data Set Summary

For the 4th quarter of FY08, there were 349 sorties flown by McConnell owned aircraft and aircrews, not including those missions flown in support of Operations IRAQI and ENDURING FREEDOM. As depicted in Figure A1 below, 72 percent were air refueling sorties, 13 percent were training sorties, coronets and contingency sorties encompassed 4 percent, 3 percent were transfer sorties, 2 percent were channel sorties, and 1 percent encompassed support sorties.

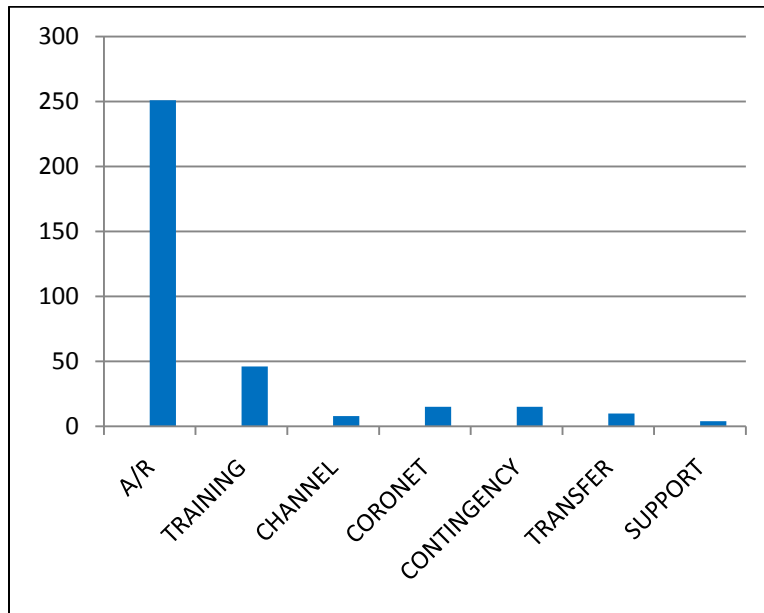


Figure A1: Number of Sorties by Type

These mission types are defined by AMCs MAF Mission ID Encode/Decode Procedures publication dated July 31, 2008 and are explained as follows:

Air Refueling (A/R): missions refueling aircraft in-flight which extends presence, increases range, and serves as a force multiplier.

Training: missions supporting training, airlift, support and other operational requirements where the use of channel, contingency, or SAAM airlift is not feasible.

Channel: missions that are common-user airlift service provided on a scheduled basis between two points. There are two types of channel airlift: a requirements channel serves two or more points on a scheduled basis depending upon the volume of traffic; a frequency channel is time-based and serves two or more points at regular intervals. These missions are in support of aeromedical evacuation (AE), cargo, and passenger (PAX) movement.

Coronet: missions in which a tanker escorts fighter aircraft as they deploy between bases. The tanker provides air refueling support, eliminating the need for the fighters to make numerous fuel stopovers.

Contingency: missions planned to support specific contingency operations or exercises. Contingency and OPLAN missions will be planned in direct support of situations requiring military operations in response to natural disasters, terrorists, subversives, or as otherwise directed by appropriate authority to protect US interests.

Transfer: missions in which aircraft are moved from one unit to another and control is relinquished such as aircraft going into and out of Programmed Depot Maintenance or aircraft rotations for highly corrosive environments.

Support: missions are movements of high-priority passengers and cargo with time, place, or mission-sensitive requirements.

Appendix B Abbreviations

AFA – Air Force Association
AFB – Air Force Base
AMC – Air Mobility Command
AMC/PA – Air Mobility Command Public Affairs
APB – Aviation Partners Boeing
API – Aviation Partners, Inc.
C_L – Coefficient of Lift
C_D – Coefficient of Drag
COA – Course of Action
DESC – Defense Energy Support Center
DoD – Department of Defense
EADS – European Aeronautic Defense and Space Company
HASC – House Armed Services Committee
HQ AF/A4 – Headquarters United States Air Force, Director of Logistics
HQ AMC – Headquarters Air Mobility Command
IL – Illinois
KS – Kansas
LLC – Limited Liability Corporation
MAF – Mobility Air Forces
NACA – National Advisory Committee for Aeronautics
NASA – National Aeronautics and Space Administration
NDAA – National Defense Authorization Act
nm – Nautical Miles
NRC – National Research Council
OG/OGV – Operations Group, Standardization and Evaluations
STC – Supplemental Type Certificates
TACC – Tanker Airlift Control Center
US – United States
USAF – United States Air Force
USAFA – United States Air Force Academy
VDT – Variable Density Tunnel
FY – Fiscal Year

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Vita

Major Ray P. Matherne entered the Air Force through the Reserve Officers' Training Corps in 1996. After graduating from Southwest Texas State University 1995 with a Bachelor of Arts in Psychology, his initial assignment was to the 12th Flying Training Wing serving as a contracts management officer in both the Headquarters Air Education and Training Command Contracting Squadron and the 12th Contracting Squadron. In 1998 Major Matherne was selected to attend Undergraduate Navigator Training (UNT) at Naval Air Station Pensacola. Following UNT he was assigned to 384th Air Refueling Squadron where he held numerous positions including assistant readiness officer, chief of squadron scheduling, and operations group executive officer. He was then selected for duty as the air mobility liaison officer for III Marine Expeditionary Forces, Camp Courtney Okinawa. Assigned to McConnell AFB a second time, his duties then included chief of KC-135 formal navigator training and chief of wing exercises and evaluations. Prior to his selection for ASAM, Major Matherne was the executive officer at the 22d Air Refueling Wing.

Major Matherne has flown or directly supported over 250 combat and combat support sorties in Operations NORTHERN WATCH, JOINT FORGE, and both ENDURING and IRAQI FREEDOM. He is a senior navigator, with over 1,200 hours in various KC-135R aircraft. His unique mission qualifications include special operations air refueling (SOAR) as well as being a member of the highly selective KC-135R/T (receiver) cadre. Following ASAM, Major Matherne will be assigned to Headquarters, European Command.

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14. ABSTRACT The 2008 National Defense Authorization Act requires the Secretary of the Air Force to task a federally funded research and development center to conduct an engineering analysis on modifying KC-135R and KC-10 tanker aircraft with winglets and submit a report to the congressional defense committees by May 1, 2009. This research summarizes the main issues that decision-makers should consider in the investment in a winglet modification program. The factors that should be included in any decision, such as fuel costs, aircraft utilization, and life-cycle costs are enumerated. Using historical flight data from AMC's Global Decision Support System-2 and fuel reports from one of AMC's super tanker wings, a cost-benefit analysis is developed to aid in the decision-making process. Although the addition of winglets to the KC-135R could reduce the future fuel expenditures between \$177 million and \$1.1 billion over the modification costs by 2042, the second-order effects to current infrastructure may diminish any potential savings achieved by the modification. Further analysis is required on a location-by-location basis to obtain the actual costs of these second-orders effects before any modification decision is made					
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