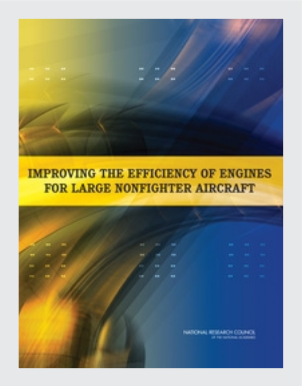

Improving the Efficiency of Engines for Large Nonfighter Aircraft

DETAILS

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IMPROVING THE EFFICIENCY OF ENGINES FOR LARGE NONFIGHTER AIRCRAFT

Committee on Analysis of Air Force Engine Efficiency Improvement Options
for Large Non-fighter Aircraft

Air Force Studies Board

Division on Engineering and Physical Sciences

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Preface and Acknowledgments

This study was requested by the Secretary of the Air Force and the Commander of the Air Force Materiel Command to identify opportunities to address the impact of rapidly increasing aircraft fuel costs. The committee sincerely hopes that this report—the culmination of an extremely focused effort on a short schedule—will enable the Air Force to make informed decisions on improving fuel efficiency for the large nonfighter aircraft inventory. We applaud the committee members for their commitment and diligence, which enabled us to complete the task successfully.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

James L. Bettner, Propulsion Consultant
Pierre Chao, Center for Strategic and International Studies
Lawrence J. Delaney, Private Consultant
Jack L. Kerrebrock, Massachusetts Institute of Technology
James O'Connor, Pratt & Whitney (retired)
Frank Pickering, GE Aircraft Engines (retired)
Charles F. Tiffany, The Boeing Company (retired)
Robert C. Turnbull, T.K. Engineering Associates, Inc.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William G. Agnew, General Motors (retired), NAE. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee acknowledges and appreciates the contribution of the members of the Air Force Studies Board (AFSB) of the NRC for developing the study statement of task in concert with the Air Force sponsor. The AFSB was established in 1996 by the National Academies at the request of the United States Air Force. The AFSB brings to bear broad military, industrial, and academic scientific, engineering, and management expertise on Air Force technical challenges and other issues of importance to senior Air Force leaders. The board discusses potential studies of interest, develops and frames study tasks, ensures proper project planning, suggests potential committee members and reviewers for reports produced by fully independent ad hoc study committees, and convenes meetings to examine strategic issues. The board members listed on page vi were not asked to endorse the committee's conclusions or recommendations, nor did they review the final draft of this report before its release, although board members with appropriate expertise may be nominated to serve as formal members of study committees or as report reviewers.

The committee is very grateful to the Air Force for its dedicated support throughout the study and for the efforts of National Research Council staff members Michael Clarke, Jim Garcia, Daniel Talmage, Carter Ford, Marta Vornbrock, Detra Bodrick-Shorter, LaNita Jones, LaShawn Sidbury, Bill Campbell, Lindsay Millard, and Dionna Ali.

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Natalie W. Crawford, *Vice Chair*
Committee on Analysis of Air Force
Engine Efficiency Improvement Options
for Large Non-fighter Aircraft

Contents

APPENDIXES

Acronyms

AAFRF	assured aerospace fuels research facility
AD	airworthiness directive
ADANS	Airlift Deployment Analysis System
AFRL	Air Force Research Laboratory
AFSAB	Air Force Scientific Advisory Board
AFTOC	Air Force Total Ownership Cost
ALBEN	augmented load-balanced exhaust nozzle
AMC	Air Mobility Command
APU	auxiliary power unit
ATOW	average time on wing
AWACS	Advanced Warning and Control System
BMW/RR	Bavarian Motor Works/Rolls-Royce
CAIG	Cost Analysis Improvement Group
CALCM	Conventional Air Launched Cruise Missile
CAMPS	Consolidated Air Mobility Planning System
CCI	capability-to-cost index
CER	cost-estimating relationship
CIP	component improvement program
CO_2	carbon dioxide
CRAF	Civil Reserve Air Fleet
CTL	coal to liquid
DER	Designated Engineering Repair
DESC	Defense Energy Support Center
DLR	depot-level reparable

DoD	Department of Defense
DOE	Department of Energy
DSB	Defense Science Board
ECM	electronic countermeasure
EGT	exhaust gas temperature
EMDP	Engine Model Derivative Program
EOC	engine overhaul costs
EPA	Environmental Protection Agency
ESPC	Energy Savings Performance Contract
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FCF	functional check flight
FOB	free on board
FOFSD	follow-on full-scale development
FSD	full-scale development
FSPC	Fuel Savings Performance Contract
FT	Fischer-Tropsch (process)
GSA	General Services Administration
HPT	high-pressure turbine
ICAO	International Civil Aviation Organization
IHPTET	Integrated High Performance Turbine Engine Technology
IPT	integrated product team
JSTARS	Joint Surveillance and Target Attack Radar System
L/D	lift/drag
LCC	life-cycle cost
LPT	low-pressure turbine
LRS	long-range strike
ManTech	Manufacturing Technology (DoD program)
MDS	mission design series (designator)
MQT	military qualification test
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NECPA	National Energy Conservation Policy Act
NO_x	nitrogen oxide
NPV	net present value
NRC	National Research Council
NRE	nonrecurring engineering

O&S	operating and support
OEM	original equipment manufacturer
OEW	operating empty weight
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
P&W	Pratt & Whitney
PAH	polycyclic aromatic hydrocarbon
PMA	Production Manufacturing Authority
R&D	research and development
RFI	request for information
ROI	return on investment
RR	Rolls-Royce
S&T	science and technology
SAF/US	Secretary of the Air Force/United States
SFC	specific fuel consumption
SiS	Share in Savings
SLEP	service life extension program
SPR	Strategic Petroleum Reserve
STOL	short takeoff and landing
T/W	thrust to weight ratio
TACC	Tanker Airlift Control Center
TER	total engine removal
TOW	takeoff weight
TRL	Technology Readiness Level
TSFC	thrust-specific fuel consumption
UAS	unmanned aircraft system
UEET	ultraefficient engine technology
USAF	United States Air Force
VAATE	Versatile Affordable Advanced Turbine Engine
WE	weight empty

Summary

THE BOTTOM LINE

The Air Force tasked the National Research Council with examining and assessing options for improving the engine efficiency of all large nonfighter aircraft in the force. Engine efficiency improvements can result in either better performance or decreased fuel consumption or some combination of the two. For purposes of this report the primary objective of modifying or re-engining Air Force aircraft with more efficient engines is to reduce fuel consumption. Attaining this objective would have two immediate major benefits: improved national security through reduced reliance on imported foreign oil, and reduced cost of supplying and operating the aircraft. However, there are a number of additional benefits and constraints to be considered. Aircraft performance improvements, reduced maintenance, improved reliability and safety, and reduced environmental impact could all be benefits. By the same token, the cost of the modifications or re-engining is a significant constraint, as is timing. While decisions should be based on economic benefit/cost analysis, they must also consider some of the benefits that cannot be easily monetized, such as performance improvements and national security. It may be the case that a greater-good argument prevails, with the decision being made on more than just economic grounds, and that the controlling variable is saving fuel—not at any cost but at a reasonable cost.

KEY FINDINGS

As a first cut, the Committee on Analysis of Air Force Engine Efficiency Improvement Options for Large Non-fighter Aircraft constructed a plot that mapped potential fuel savings for each aircraft type versus the remaining life, using data provided by the Air Force (Figure S-1). Figure S-1 shows the most favorable re-engine option in terms of improved efficiency and reduction in fuel consumption and plots the calculated fuel savings based on 2005 fuel consumption for each platform against the expected remaining life (AFOTC, 2006). A bubble's diameter is proportional to the number of that type of platform in the overall fleet.

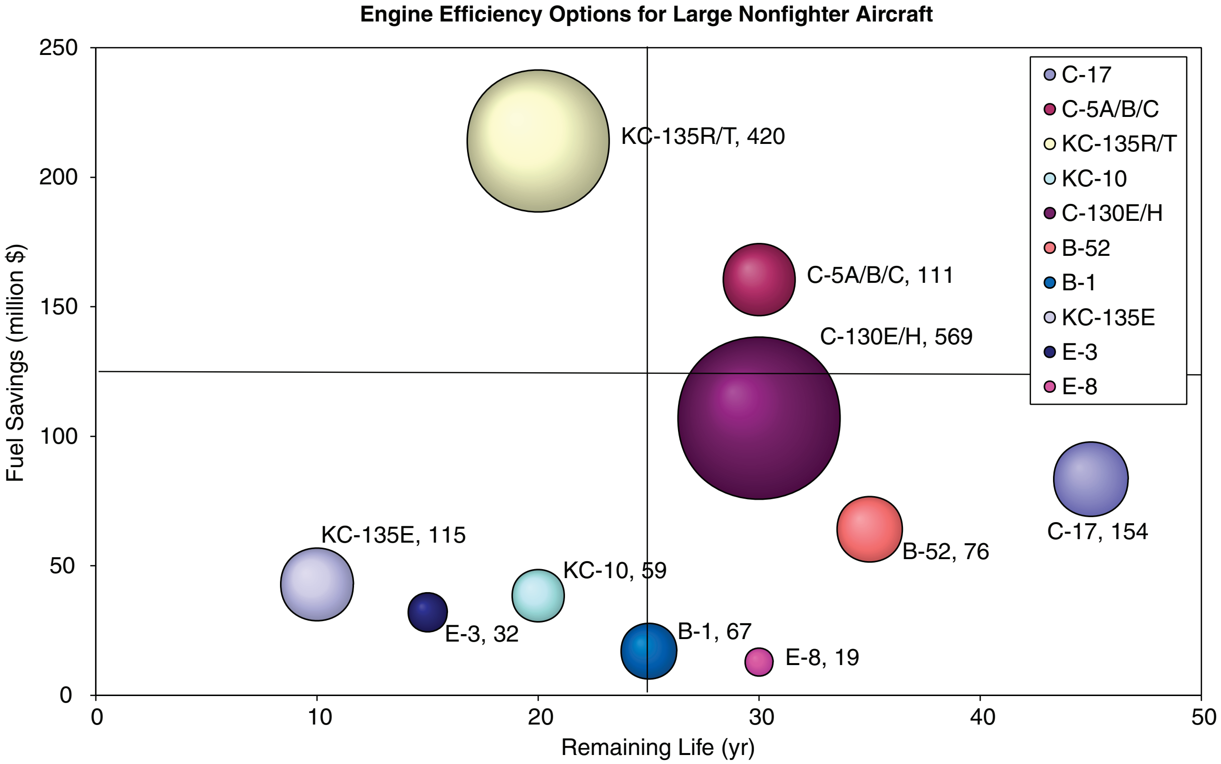

FIGURE S-1 Potential fuel savings by selected large nonfighter aircraft (based on a fuel price of $2.14 per gallon). SOURCE: Committee generated.

The committee conducted a constrained cost/benefit analysis for each viable engine/airframe modification or re-engining candidate.[1] The committee concluded there are a number of modification and re-engining options that deserve careful consideration and might pay for themselves within the remaining life of the engine/aircraft. Table S-1 summarizes the committee's analysis of re-engining options. Table S-2 summarizes the committee's analysis of engine modification options.

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[1] After the prepublication version of the report was released on January 31, 2007, errors were discovered in the input data used by the committee to estimate net present values. These errors affected the results shown in several tables and figures in Chapter 5, Appendix G, and the Summary. In addition, the committee had made these estimates for the various aircraft/engine combinations using a mix of cost estimating relationships (CERs) and market data (if the latter were available). This mixed method meant that some of the aircraft/engine cost estimates based on CERs were being compared with other estimates using both CERs and market data. In redoing these calculations using reconfirmed input data, the committee decided to base the cost estimates on CERs only since market data were not available for all engines and could in any case vary significantly over time and by source. The members of the committee with extensive industry backgrounds (engine companies) agreed that the market data should be removed from the analysis. The reasoning was straightforward: Market data are just that—they represent the opening for price negotiation and not a precise sales price to be published. The Air Force always evaluates and negotiates sales price of a proposal at best and final. Each table and figure affected by the committee's reanalysis is identified by a footnote. While the new data did not make Air Force decisions to re-engine or upgrade more likely or less likely, nor change the recommendations offered in this report, the revised analysis is more correct, more realistic, and more useful to the Air Force as input to its decision-making process.

TABLE S-1 Re-engining Analysis Results[a,b]

Aircraft	Current Engine[c]	Re-engine Candidates	Years to Recoup Costs[d,e]
C-130H	T56 (T56)	AE 2100, PW150	12.4-17.7
B-1	F101	F119/5.0	33.5->60
E-3	TF33 (JT3D)	CFM56-2B-1, JT8D-219, CFM56-7B22	13.0-16.5
KC-135D/E	TF33 (JT3D)	CFM56-2B-1, JT8D-219, CFM-56-7B22	20.6-31.6
B-52	TF33 (JT3D)	F117-PW-100 (4), CF34-10A (8), CFM56-5C2 (4)	12.6-16.1

[a] Entries corrected after release of the January 31, 2007, prepublication version of the report.

[b] The committee emphasizes that the analyses and the results presented in this table are not intended to be definitive assessments of the various options. A more extensive analysis may show shorter times to recoup costs, and such analysis should be conducted for selected options prior to any final decision by the Air Force.

[c] Military designations shown. Designations in parentheses are commercial engine equivalents where they exist.

[d] Shortest time to recoup costs (in years) of any option with fuel at $2.50 per gallon and fuel inflation rates of 3, 6, and 9 percent.

[e] Despite presentation of the analysis results as precise numbers, it is imperative that they be viewed and used as approximate estimates, each surrounded by some amount of uncertainty.

TABLE S-2 Engine Modification Analysis Results[a]

Aircraft	Current Engine	Years to Recoup Costs[b,c]
KC-135R/T	CFM56-2B-1	36.6->60
C-130H	T56	12.6-17.8
B-1	F101	7.4-8.0
KC-10	CF6-50	3.8

[a] Entries corrected after release of the January 31, 2007, prepublication version of the report.

[b] Shortest time to recoup costs (in years) of any option with fuel at $2.50 per gallon and fuel inflation rates of 3, 6, and 9 percent.

[c] Despite presentation of the analysis results as precise numbers, it is imperative that they be viewed and used as approximate estimates, each surrounded by some amount of uncertainty.

The committee's analysis did not indicate that the cost of re-engining the KC-135D/E could be recouped in less than 20 years.[2] However, as discussed in the report, the committee recommends that the Air Force approach re-engining of the aircraft powered by the various models of the TF33 engine on a holistic basis, with the goal of removing the engine from the inventory.

The committee examined environmental considerations and/or the benefits of each action. In addition, several other approaches to saving fuel were studied, including aircraft winglets, laminar flow nacelles, optimization of operations, engine build practices, information use, and engine water washing. The committee examined the potential impact of alternative fuels[3] and engine science and technology programs. It also evaluated several acquisition, financing, and support options.

The committee's analysis was not a complete benefit/cost analysis since not all benefits associated with engine modifications, re-engining, and airframe modification to achieve fuel savings or reliability,

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[2] The committee's analysis did not attempt to account for the residual value of engines (which, in general, could improve the case for re-engining or engine modification) after re-engined airframe retirement. If engine residual value were taken into account, the cost of re-engining the KC-135D/E could possibly be recouped in less than 20 years.

[3] These fuels have not come into widespread commercial use in the United States partly because of their cost, but with rising petroleum cost and with increased production volume, some alternative fuels are beginning to look competitive, and technology is improving. The fact that Sasol in Africa, with FT fuel, and others in Canada, with tar sands, are in production is promising.

maintainability, availability, and/or performance improvements were monetized. It did not attempt to account for the residual value of engines after re-engined airframe retirement or for any national benefit from reduced dependence on imported foreign oil. No such analysis was feasible within the time constraints of this study. Such an analysis should be undertaken for selected options by the Air Force prior to any final decision. In particular, the Air Force should consider the potential for cost-saving or capability-enhancing changes to force structure that would be enabled by re-engining existing platforms.

GENERAL OBSERVATIONS

Some general observations apply across the entire fleet. First, the value of ensuring that everyone in the Air Force understands the importance of fuel conservation cannot be overstated. Fuel improvements or impacts must be part of every major decision. The C-130 Large Aircraft Infrared Countermeasures (LAIRCM) modification serves as an excellent example. The antenna for the module was mounted externally rather than flush to save installation time and money. Unfortunately the added drag significantly increases fuel consumption on the C-130.

Second, similarities and commonalities between commercial and Air Force engines present opportunities to increase Air Force fuel efficiency. Commercial engines or derivatives (such as the CFM56, F108, CF6-50, CF6-80, and PW2040) are installed on several Air Force weapon systems (such as the C-135R/T, B-1, KC-10, C-5, and C-17). As commercial users modify their engines in anticipation of paybacks, those modifications should be evaluated for incorporation into the military fleet. The military may also benefit from much of the nonrecurring engineering work that will have already been done.

Third, while Air Force aircraft are in depot maintenance with their engines removed to facilitate other maintenance, modifications or upgrades could be installed with no additional downtime or maintenance for the operational users of the weapon system. Rotatable pools of engines for exchange during the depot maintenance process could help exploit these opportunities.

Fourth, other commercial practices present the Air Force with opportunities to save on fuel and operating costs. Examples include engine build policies that maximize fuel efficiency, parts replacement policies, water washes of engines, and scheduling and operating procedures optimized to save fuel.

Fifth, the Air Force could resort more often to competition to save money. For example, it could competitively procure all new engines and parts from the manufacturers and determine the relative costs and benefits of maintaining engines in organic Air Force facilities or on contract and, for the latter, compete maintenance across all providers of such services.

KEY RECOMMENDATIONS

The committee's key recommendations are listed below. Supporting discussion for these recommendations is provided in Chapters 1-9 of the report along with additional recommendations. The recommendation numbers here in the Summary correspond to their numbers in the body of the report.

Proposed Engine Modifications and Re-engining

Recommendation 3-3. The Air Force should pursue re-engining the C-130H on a priority basis, since this aircraft is one of the largest users of fuel in the Air Force inventory. The Air Force should use a competitive bid procurement process to provide the background for a decision on the C-130H models between the AE 2100 and PW150 engine options, either of which would appear to be acceptable on a technical and performance basis, and it should review the economics of engine efficiency upgrades (engine modifications) to the older models with a shorter remaining service life.

Recommendation 3-5. In general, where commercial engine/airframe counterparts exist (KC-10/DC-10, F103/CF6-50, KC-135/B-707, TF33/JT3, F-108/CFM56, etc.), Air Force engine and weapons systems planners, managers, and policy makers should closely monitor the engine's original equipment manufacturers' (OEMs') and commercial operators' activities and actions relative to re-engining and engine modification as a measure of the cost/benefit for these activities.

Recommendation 3-6. Since the C-17/F117 system is the largest consumer of fuel, the Air Force should conduct an engine model derivative program (EMDP) study with Boeing and Pratt & Whitney to determine possible fuel savings, implementation costs, and a schedule that would give the best return on investment for the Air Force.

TF33 Series Powered Aircraft

Recommendation 4-1. The Air Force should approach re-engining of the aircraft powered by the various models of the TF33 engine on a holistic basis with the goal of removing the engine(s) from the inventory.

Recommendation 4-2. The Air Force should immediately conduct for each TF33-engined weapon system an internal review and competitive re-engining study that looks at fuel savings, operational capabilities, and maintenance costs as figures of merit in order to select the best option.

Other Considerations

Recommendation 6-5. The Air Force should study optimization and, where it has already done so, accelerate the implementation of optimization in all aspects of its operations, especially as it relates to maintenance and overhaul and to the scheduling of its cargo, passenger, and tanker fleets.

Recommendation 6-6. The Air Force should undertake a review of maintenance requirements and how they affect fuel efficiency and/or fuel conservation. Additionally, it should have in place an organizational structure that will have the focus and authority to establish maintenance requirements across all operations. Additionally, the Air Force should undertake a comprehensive review of information systems to assure that repair histories and reliability information are being utilized in a holistic manner and being transmitted to the appropriate organizations—that is, those that have oversight responsibility for efficient operations and the ability to implement the required actions. Critical to this recommendation is the establishment of fleet manager programs to oversee the entire maintenance operation, both line and shops, and the development of a comprehensive information system to monitor the effectiveness of maintenance actions and fleet performance. The ability of an integrated database to inform a cognizant organization that has a say about the outcome of maintenance, whether in the field or in the shop, is a critical factor in achieving operational fuel efficiency. Lastly, the maintenance entity must be organized along the flow of information to assure that there is top-down and bottom-up access to all the information that is required to maintain the equipment.

Alternative Fuels

Recommendation 7-4. DoD should take steps beyond the B-52 flight demonstration to reaffirm its long-term commitment to synthetic fuels for its fleet of aircraft. This includes qualifying an FT fuel specification and fully certifying aircraft re-engined with, for example, CFM56 and large tanker platforms such as the KC-135R/T, C-130, and KC-10.

Recommendation 7-6. DoD should, over the period FY08-FY15, put into place a comprehensive program of candidate fuel qualification strategy comprising four phases: R&D, system demonstration, transition and deployment, and operations and support (see Figure 7-3). This work should be funded at $15 million per year.

Technology Preparedness and Insertion

Recommendation 8-1. The Air Force should review and amend the Versatile Affordable Advanced Turbine Engine (VAATE) plan and its engine development programs, as appropriate, to provide an explicit emphasis on technology to improve fuel efficiency and reduce operational costs, to transition those improvements to fielded, high-bypass-ratio engines, and to consider research aimed at the reduction of particulate, hydrocarbon, sulfur, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and noise emissions by the DoD systems.

Recommendation 8-4. The Air Force and DoD should reinvigorate the component improvement program (CIP) and the propulsion capability enhancement programs and combine the responsibility for component improvement, sustainment, and fuel burn under one budget authority to allow it to capture opportunities to reduce fuel burn and cost.

Recommendation 8-5. The Air Force and DoD should restore turbine engine S&T funding to the original level necessary to execute the VAATE plan (with recommended changes), with particular emphasis on reinvigorating engine demonstration programs aimed at rendering new technologies ready for transition to fielded engines.

Acquisition, Financing, and Support

Recommendation 9-1. The Air Force should adopt the following options right away: (1) maintaining all commercial derivative engines to FAA standards, (2) competing all maintenance contracts, (3) creating a line item in the defense budget, and (4) implementing a "fuel-savings performance contract" strategy.

Recommendation 9-2. The Air Force should aggressively evaluate the following options to determine their true utility: (1) re-engining Air Force aircraft with commercial engines and leasing or reselling the engines when the airframe is retired, (2) creating a spare engine and parts pool, (3) leasing engines on a long-term basis, and (4) leasing engines on a short-term basis.

1

Introduction

STUDY ORIGIN

> The prices of gasoline should serve as a wake-up call to all of us involved in public office, that we have got an energy security problem and a national security problem, and now is the time to deal with it in a forceful way.
>
> —President George W. Bush, May 3, 2006

This report responds to a United States Air Force (hereinafter "the Air Force") request to review all large nonfighter aircraft and develop a list of candidate aircraft that would benefit the most from engine efficiency improvement, to include re-engining and, in particular, reducing the fuel burden. Box 1-1 provides the study's statement of task.

In February 2006, representatives from the Air Force and the Air Force Studies Board (AFSB) of the National Research Council (NRC) met to discuss the study parameters and finalize the above statement of task. During the course of this meeting and subsequent discussions, additional parameters for the study evolved, so that the task would include enhancement of aircraft performance and efficient completion of missions. For many military aircraft, the airframe lifetime encompasses a number of engine technology improvement cycles, and these aircraft could benefit accordingly from performance improvements such as shorter takeoff distance, increased range, lower exhaust gas temperature, higher altitude operation, and greater auxiliary electric power capability.

OVERVIEW OF AIR FORCE FUEL CONSUMPTION AND COST STRUCTURE

Reducing energy consumption is now a strategic goal of the Department of Defense (DoD):

> The Department of Defense is now serious about developing a strategic approach to energy consumption and conservation. No longer will energy be considered a free commodity. . . . Both Defense Secretary Donald Rumsfeld and Deputy Defense Secretary Gordon England are initiating steps to galvanize new actions across the department. . . . The Secretary wants to ensure that the Defense Dept. is pursuing in-

BOX 1-1
Statement of Task

The NRC will:

Review all large, nonfighter aircraft and develop a list of candidates that would benefit most from engine efficiency improvements or re-engining.

Assess and leverage all relevant past re-engining studies.

Evaluate life-cycle cost-benefits for each candidate, including fuel savings, reliability, maintainability, logistics and sustainment support. Consider safety, environmental, and operational implications.

Recommend affordable re-engining and/or engine life extension improvements.

Determine whether multiplatform solutions are possible for reducing inventory footprint.

Develop implementation strategies to include conventional as well as innovative acquisition, financing and support concepts.

> novative initiatives in the areas of fuel-efficient vehicles, advanced battery technology and hybrid power trains. . . . [Deputy Secretary] England is overseeing the issuance of a new department-wide guidance, focusing on concrete steps the Pentagon can implement to conserve energy. (Pudas, 2006, p. 42)

The above memorandum effectively institutionalizes energy conservation within DoD, and it is expected that the Air Force will follow with a set of guidelines for fuel conservation. As shown in Figure 1-1, in 2005 DoD consumed 97 percent of all fuel used by the U.S. government (Sega, 2006), or 5.6 billion gallons (DESC, 2005). Within DoD, the Air Force utilized the most fuel (53 percent), approximately 3.0 billion gallons (Sega, 2006; DESC, 2005).

As shown in Figure 1-2, in 2005 aviation fuels accounted for 89 percent of all Air Force fuel, totaling approximately 2.7 billion gallons (Sega, 2006; DESC, 2005). Nonfighter aircraft accounted for approximately 64 percent of total Air Force aviation fuels (Sega, 2006), or approximately 1.7 billion gallons (DESC, 2005). Within the large nonfighter aircraft fleet, 10 aircraft families account for 90 percent of the total utilization of nonfighter fuel, as shown in Table 1-1. For this reason, the study reviewed each of these aircraft to determine whether there are engine improvements or, possibly, aerodynamic improvements that can be incorporated to reduce the overall fuel burden on the Air Force. The study also examined potential savings afforded by increased operational capabilities and maintenance measures that might lead to lower sustainment costs.

In fact, because many nonfighter aircraft have been in service for a long time, the application of modern engine and aerodynamic technology could dramatically improve fuel efficiency.

However, all benefits must be balanced against the life-cycle costs of these new technologies over the remaining life of the aircraft. Incorporating engine improvements or re-engining an aircraft can impact all major aircraft systems. Moreover, the cost of implementation may also include reanalysis,

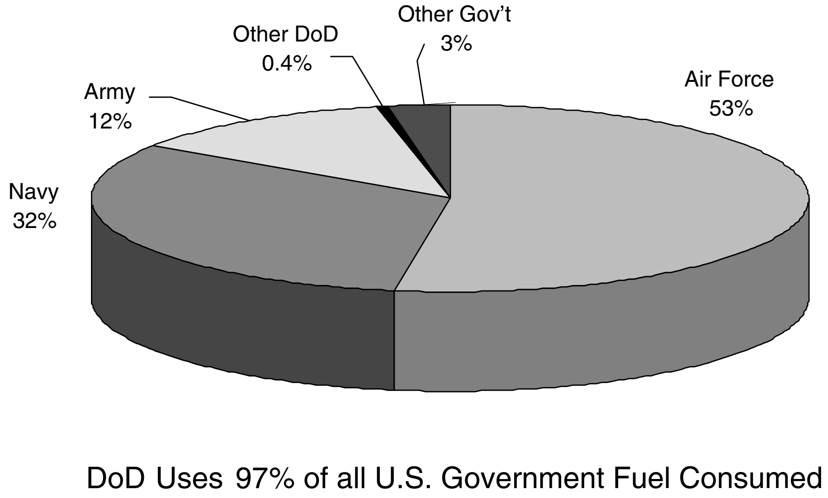

FIGURE 1-1 Fuel usage by DoD in 2005. SOURCE: Sega (2006).

redesign, or recertification of other major aircraft systems to include cockpit controls, bleed air systems, hydraulic systems, electrical systems, aircraft structure, as well as maintenance operations and technical publications. Offsetting these potentially high nonrecurring costs has been, and remains, a high hurdle to the incorporation of desired improvements.

To better understand when and how re-engining programs make economic sense, it is important to understand both how the Air Force consumes fuel and how it incurs cost. Although much of the material discussed below has been stated in other publications, it is worthwhile for the sake of context to restate some key facts.

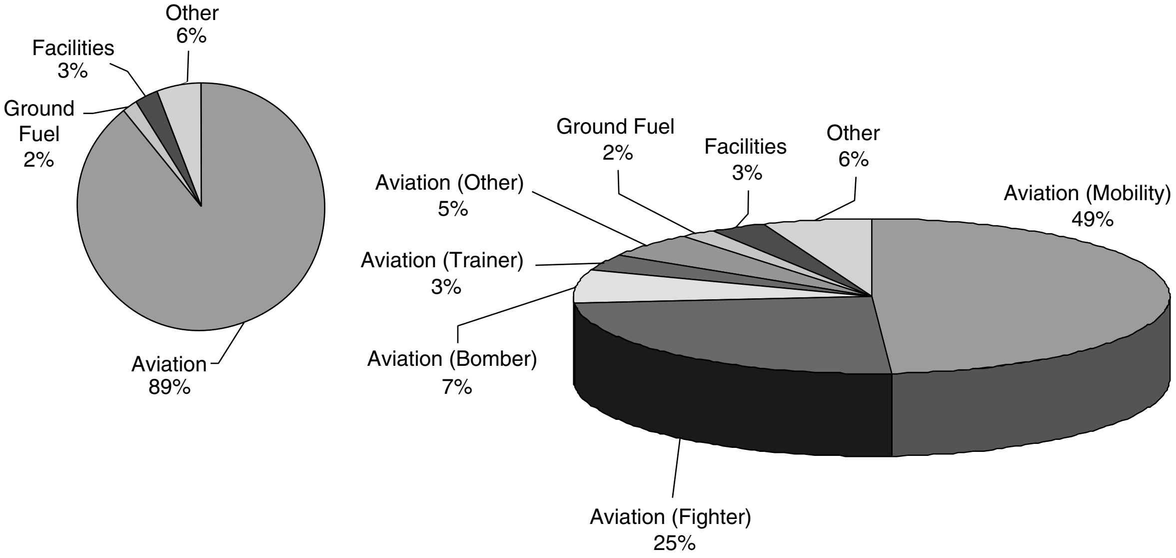

FIGURE 1-2 Distribution of fuel usage within the Air Force in FY05. SOURCE: Sega (2006).

TABLE 1-1 Large Nonfighter Aircraft Candidates for Re-engining and Engine Modification

Fuel Use Rank	Aircraft	Number of Aircraft	Number of Engines	Engine Model[a]	Fuel Consumed (million gal)	Share (%)	Cumulative Fuel Share (%)
1	C-17	154	670	F117 (PW2040)	427	25	25
2	KC-135R/T	420	1,744	F108-100 (CFM56-2)	335	20	45
3	C-5	111	612	TF39	225	13	58
4	KC-10	59	204	F103 (CF6-50)	160	9	67
5	C-130H	272	2,093	T56-15	113	7	74
6	B-52	114 (76 active)	855	TF33-103 (JT3D)	88	5	79
6	B-1	67	438	F101	85	5	84
8	KC-135D/E	115	662	TF33-102 (JT3D)	44	3	87
9	E-3	32	174	TF33-100 (JT3D)	35	2	89
10	E-8	19	96	TF33-102C (JT3D)	22	1	90

[a] Term in parentheses is military designation.

SOURCE: Adapted from Over (2006) and AFSAB (2006); fuel consumed is from DESC (2005).

Important factors that determine the total peacetime fuel burn of the Air Force large nonfighter aircraft fleet include fleet size, per-flying-hour fuel consumption, and the average annual usage rate in peacetime flying hours per aircraft per year. The annual fuel burn of each aircraft type is the product of these three factors.

The total Air Force fleet consists of approximately 5,986 aircraft and includes approximately 2,019 large nonfighter aircraft, which with the exception of bombers, are further categorized primarily as tankers, trainers, and transports.[1,2] In addition, the Air Force fleet, as a whole, flies approximately 2 million accumulated flying hours per year.[3,4]

The overall cost structure of the Air Force can be divided into (1) fixed annual costs and (2) variable costs. The fixed annual costs are incurred each year regardless of whether and how the Air Force uses its aircraft and people.[5] In contrast, variable costs are incurred only when the Air Force conducts missions for, or in direct support of, military operations. The estimated fixed costs account for approximately 95 percent of the Air Force's annual budget.

The Air Force cost base is dominated by fixed costs because the Air Force flies its aircraft an average of 358 flying hours per aircraft per year. By contrast, a typical commercial airline flies its aircraft an average of 3,000 hours per aircraft per year. The reason for the striking difference between the Air Force and commercial practice is very straightforward. In commercial practice, an idle airplane means lost revenue and no return on investment. By contrast, the military must prepare for wars that it hopes

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[1] As of September 30, 2005, according to "The Air Force in Facts and Figures—2006 USAF Almanac" in *Air Force Magazine*, May 2006. The two total aircraft fleet numbers include the Total Active Inventory and Primary Aircraft Inventory and include the inventories of the active-duty fleet, the Air National Guard, and the Air Force Reserve Command (AFM, 2006).

[2] "The Air Force in Facts and Figures—2006 USAF Almanac" lists additional nonfighter aircraft categories: helicopters; reconnaissance/battle management/command, control, computers, and intelligence aircraft; and special operating forces aircraft (AFM, 2006).

[3] According to "The Air Force in Facts and Figures—2006 USAF Almanac." Further breakdown of total and average flying hours per type of aircraft may be designated sensitive information and not for public release.

[4] Air Force (A9) databases do not differentiate between combat flying hours and training flying hours. Further, generally speaking, discrepancies between actual and programmed flying hours provide a rough indication of hours required to support contingency operations.

[5] Not to be confused with sunk costs, which are costs already paid for.

never come. This means that the military must be equipped with the right kinds and numbers of equipment to prevail in wartime. At other times, these assets are largely idle, with the use rate being held to the minimum necessary to maintain an adequate level of training for personnel.

For example, the committee estimated if the fuel consumption of the entire non-fighter aircraft fleet could be reduced by 25 percent, based on 2005 fuel usage, that would equal a reduction in fuel consumption of approximately 0.5 billion gallons of fuel per year. At the Defense Logistics Agency delivered fuel price of $2.53 per gallon, this represents just under $1.14 billion per year, or approximately 1 percent of the Air Force's total annual budget (Harrison, 2006).

The committee concluded that while re-engining can lead to reductions in Air Force fuel consumption, it is unlikely to pay for itself for most weapons systems at today's fuel prices.[6] Exceptions to this are cited in the text.

LESSONS LEARNED FROM PREVIOUS RE-ENGINING PROGRAMS

Commercial Re-engining Programs

In recent history only one aircraft re-engining exercise was conducted by major airlines of the U.S. air transport industry. DC-8-60 series aircraft were re-engined by one major passenger airline and one major freight carrier. The experience of the passenger airline that conducted a conversion of JT3D-3 to CFM56-2 engines on DC-8-61 aircraft indicated that the standard net present value (NPV) calculation of the cost/benefit aspects directly tied to the program was relatively accurate. The program met all of its expected financial and operational goals to the point that the trip costs for the newly re-engined DC-8-71 were the best of all fleets except for the 767, which was the latest technology aircraft in delivery to the airline. The DC-8-61/JT3D-3 combination proved to be an ideal candidate for re-engining because the DC-8-61 airframe had the structural capability required to allow the use of the larger engine, and the CFM56-2 turbofan engine provided substantial efficiency, performance, and noise reduction improvements over the first generation of turbojet JT3D-3 engines.

Military Re-engining Programs

Similar to the experience of the passenger airline program to convert JT3D-3 to CFM56-2 engines on DC-8-61 aircraft, the KC-135 re-engining program indicated that performance improvements were accurate. However, the standard NPV calculation of the cost/benefit aspects directly tied to initial program justification could not be substantiated. Significant changes in quantities of aircraft and extensions of the modification program reduced the benefits that had been projected. That being said, and although force structure and operational utilization are not within the scope of this study, the data clearly indicate a dramatic increase in mission utilization for KC-135 tanker aircraft with the new CFM56-2 (F108) engines. Re-engining programs are much more involved than adding new engines on the wing.

Complexity of Re-engining Aircraft

There is a general lack of understanding of the magnitude and complexity of any re-engine program. A re-engine program affects just about every system on an aircraft (electrical, hydraulic, pneumatic,

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[6] Allowing for force structure trade-offs could lead to substantially different results and conclusions. This is addressed briefly in Chapter 6, in the section "Other Considerations."

aerodynamic flight controls, avionics, and structural). In addition to modifications to the aircraft, a significant effort is required to revise required technical manuals (performance, aircrew, maintenance, training, and repair) as well as to update support equipment, initial spares, maintenance concepts, and engineering substantiation analyses. Appendix D contains a sample work breakdown structure. Even if the selected engine is used in a commercial in-production aircraft, the engine accessories will have to be modified to meet military mission requirements. Even engines of the same thrust range will require a significant analysis and certification effort, whether it is a certification to civilian or military standards. Because a re-engine program impacts so many aircraft systems, obsolete and line replaceable units having short mean time between failures are also replaced with newer alternatives and add to the cost and planning burden for the modification.

Program Schedule and Cost

Aircraft, engines, and weapons systems are designed as an integrated system to provide optimum performance and characteristics for planned missions. It is highly probable that unexpected costs and/or operational implications are likely to accrue from any change to the engines no matter how much planning and analysis have been committed to the development of such a program. These risks can be mitigated by the involvement of all of the organizations, including engineering, maintenance, material, flight operations, technical publications, training, and finance, affected by the program. This multiorganizational approach will help to forestall program surprises but is an impediment to rapid action in the face of high-priority economic, operational, or regulatory action demands.

For various reasons, the Air Force was unable to take advantage of optimum schedules or quantities for the acquisition and installation during the KC-135 re-engine program. Yearly purchases were less than best economic quantity, and schedule stretchouts increased total program costs. Multiple changes to production quantities and schedules further increased costs. These, in turn, led to increased acquisition costs, a longer payback period, and fewer modified aircraft.

Potential for Future Re-engining Programs

Commercial Re-engining

Airline experience has demonstrated that it is unlikely that next-generation commercial aircraft will lend themselves to re-engining campaigns in the near term, because the engines and airframes are so highly optimized to meet service requirements, the benefits of engine technology is not improving sufficiently to justify significant expense, and the structural and certification constraints impose a significant cost burden that will be difficult to overcome. In addition, commercial users routinely modify their engines to take advantage of new technology, making a new engine less beneficial than it would otherwise be.

Military Re-engining

Conceptually the potential for re-engining large, nontactical military aircraft remains attractive because of the low utilization and consequently longer service life of those weapons systems, the probability of major advancements in engine technology during that extended service life, and because mission suitability generally transcends financial justification as the primary analysis criterion.

In this study, the life-cycle cost (LCC) of incorporating a new engine is based on the best estimates of fuel savings, maintenance cost savings, nonrecurring engineering costs, certification cost, and cost of incorporation of the improvement. However, the life-cycle cost analyses do not take into account many of the enhanced operational capabilities for tactical aircraft resulting from technology improvements. For example, performance improvements such as those that might allow aircraft to operate on shorter runways are not quantified in the economic portion of this study because they are beyond its scope.

FORCE STRUCTURE FOR FUTURE STUDY

The study did not attempt to evaluate the financial and fuel savings that might be achieved by reshaping the force to take best advantage of the new capabilities of re-engined aircraft. Re-engining some aircraft might cause compounding effects beyond gains in fuel efficiency for the aircraft themselves. Those effects might lead to much larger reductions in fuel consumption for the Air Force as a whole. For example, tankers fly in support of other aircraft, particularly fighters and bombers, and the fuel consumption of the tanker fleet is related to the scale and usage of the fighter and bomber fleets. If re-engining could enable operational improvements to the bomber fleet, those operational improvements might have various downstream effects. For example, the reduced fuel burn would reduce the amount of fuel the bombers would have to upload from tankers, perhaps allowing a smaller tanker fleet. Further deliberations on Air Force force structure adjustments are beyond the scope of this study. However, force structure modifications might offer the Air Force an important mechanism for reducing fuel consumption and for making the economic case for re-engining. Any such changes might alter the findings, conclusions, and recommendations of this and previous studies. A follow-on study could reevaluate re-engining options for large nonfighter aircraft by pointing out explicitly how re-engining would allow the Air Force to alter its current and planned force structure to reduce overall fuel consumption and save money, while preserving the ability to execute the full range of missions required of it.

While the present study benefits from many earlier engine improvement and re-engining studies conducted by the Air Force, subcontractors, and independent committees, it is unique in that it covers the entire fleet of nonfighter aircraft and utilizes consistent assumptions and analysis techniques.

ADDITIONAL CONTEXT

Previous Re-engining Studies

As shown in Table 1-2 and Appendix C, the Air Force has sponsored a number of evaluations over the past two decades regarding validation, improvement, or replacement of engines for existing nonfighter aircraft. Many of the studies were motivated by the aging of the fleet or technological advancement and tended to focus on specific aircraft models, including the B-52, KC-135, E-3, E-8, and C-130.They used a variety of calculations to arrive at the cost of fuel in their cost/benefit analyses.

Indeed, the results of past studies generally have shown that engine replacement for some models of aircraft, such as the KC-135, could not be justified by cost saving alone. To a great extent, the effectiveness of any weapon system depends on the suitability of its technology for the mission requirements. Because of significant advancements in electronics and avionics over the past two decades, all of these aircraft have benefited from technical systems upgrades, making them superior weapons systems for their assigned missions. The cost effectiveness of modification, upgrade, or replacement of existing power plants should therefore be periodically reviewed.

TABLE 1-2 Previous Studies on Re-engining Aircraft

Study	Author	Date
Technology Options for Improved Air Vehicle Fuel Efficiency	Air Force Scientific Advisory Board	2006
B-52 Propulsion Capability Study	ACSSW/PRSS New Engines	2005
C-130 Enhanced Capabilities	Snow Aviation International	2005
AC-130U Alternate Engine Summary Report	Macaulay Brown/UTC	2005
Task Force on B-52H Re-engining (Revised and Updated)	Defense Studies Board	2004
TF33 Re-engine Fleet Look-Ahead	Oklahoma City Air Logistics Center	2004
The Air Force KC-767 Tanker Lease Proposal: Key Issues for Congress	Congressional Research Service	2003
B-52 Re-engine Study Report	Boeing/Hannon Armstrong	2003
B-1B Re-engining, Mission Flexibility (for Maj Gen Dan Leaf)	Boeing	2002
KC-135 Engine Modernization Program: LCC Analysis	Boeing	2000
TF33 Propulsion System Roadmapping Study	Pratt & Whitney	1998
Findings of the B-52H Re-engining Cost IPT	SAF/Financial Management	1997
Analysis of Aerial Tanker Re-engine Programs	Congressional Budget Office	1984

NOTE: For more information, see Appendix C.
SOURCE: Committee generated.

Air Force Scientific Advisory Board Study on Technology Options for Improved Air Vehicle Fuel Efficiency

As shown in Figure 1-3, the AFSAB stated that the United States currently depends on foreign sources for 63 percent of its annual fuel utilization (AFSAB, 2006; Karagozian, 2006).

That dependency is projected to grow to 70 percent by 2025. The government used 1.7 percent of the total annual fuel consumption of the United States in FY03. As already stated in the discussions accompanying Figures 1-1 and 1-2, DoD was the largest fuel consumer, with 97 percent of government fuel usage attributed to DoD. Within DoD, the Air Force used 53 percent of the total fuel. Finally, as

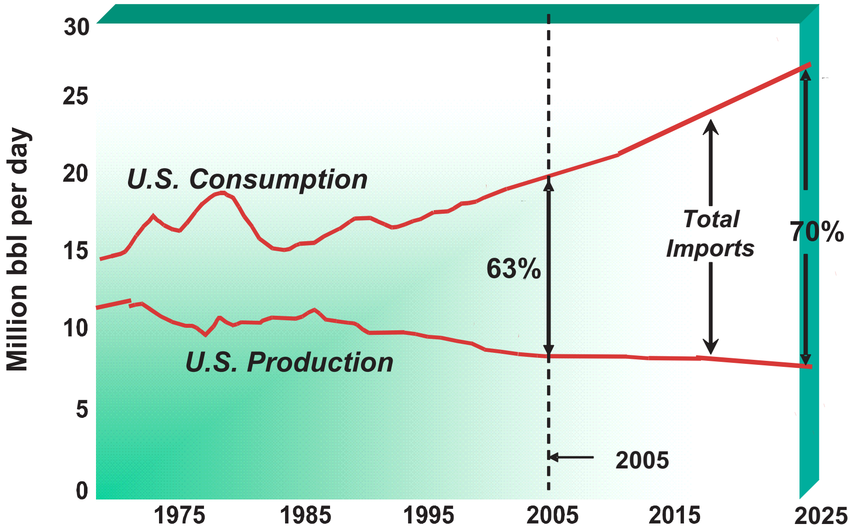

FIGURE 1-3 Sources of crude oil consumed by the United States. SOURCE: AFSAB (2006) and Karagozian (2006).

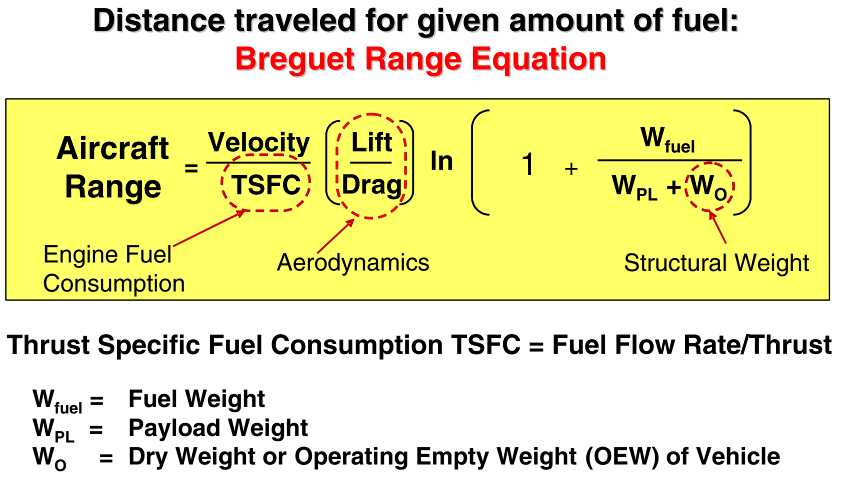

FIGURE 1-4 Fuel efficiency as defined by the Breguet range equation. SOURCE: AFSAB (2006) and Karagozian (2006).

shown in Figure 1-2, 89 percent of the total Air Force consumption was dedicated to aviation fuels, while nonfighter aircraft within the Air Force inventory consumed 72 percent of the aviation fuel.

The AFSAB study indicated the actual cost of fuel to the Air Force is $2.14 per gallon while the cost to deliver that fuel in mission applications varies significantly. For example, the cost to transport fuel for in-flight delivery via tanker is $24.23 per gallon, for a fully burdened cost of $26.37 per gallon (AFSAB, 2006; Karagozian, 2006).

When seeking technology alternatives for improved engine efficiency, the Breguet range equation, shown in Figure 1-4, provides a convenient method for assessing the effects of fuel consumption, aerodynamics and structural characteristics considerations on overall aircraft fuel efficiency.

Figure 1-5 illustrates the relative cost/benefit of alternative means to achieve fuel efficiency, as determined by AFSAB. Table 1-3 provides the AFSAB's view of additional cost/benefit relationships of various methods to enhance fuel efficiency.

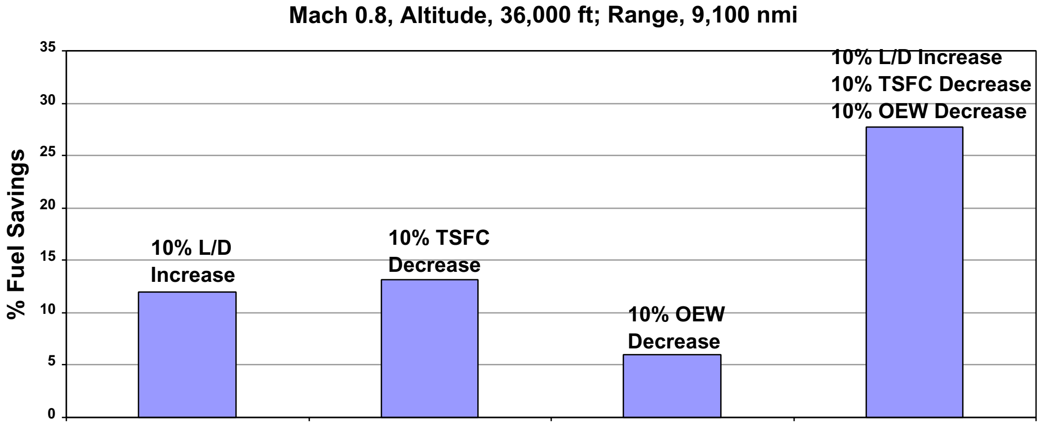

FIGURE 1-5 Potential fuel savings for transports. SOURCE: AFSAB (2006) and Karagozian (2006).

TABLE 1-3 Factors Leading to Possible Fuel Savings

Solution	Time Span[a]	Δ Fuel Efficiency (%)	Δ Fuel Efficiency/Cost
Aerodynamic			
Wing retrofits, including winglets	Near term	5	High
Major wing redesign	Mid term	10	Medium
Active flow/separation control	Mid term	5	High
Revolutionary configurations, including BWB, oblique wing, and hybrid airships	Far term	25	Medium
Structural and material			
Integrated vehicle health monitoring	Near term	1	Medium
Structural design and optimization and active wing control	Mid term	15	Medium
Advanced design and analysis tools	Far term	10	High
Operational			
Enhance tracking and reporting of Air Force fuel utilization	Near term	3	High
Optimize aircraft operations including engine out taxi, APU usage, optimal route planning, and RVSM	Near term	5	High
Increased use of simulators and distributed mission training	Near term	5	Medium
Autonomous formation flight	Mid term	15	High
Fuels[b]			
Fischer-Tropsch fuel from coal	Near term	1	High
Oil shale	Mid term	1	Medium
Other hydrocarbons, including LNG, ethanol blends, and biodiesel	Mid term	1	High
Hydrogen for fuel cells in APUs	Mid term	1	Medium
Biomass, including black liquor fuels	Far term	1	High
Hydrogren fuel for turbine engines	Far term	5	Medium

NOTE: BWB, blended wing-body; APU, auxiliary power unit; RVSM, reduced vertical separation minima.

[a] "Near term" is defined as the period from the present out to 5 years; "mid term" is 5 to 15 years in the future; and "far term" is implementable beyond 15 years in the future. For each solution, both the approximate benefit (ΔFE, or the change in the fuel efficiency metric) and the benefit-to-cost ratio (ΔFE divided by a rough estimate of cost) are listed. Each technological concept identified here has, approximately, a high or medium impact based on the benefit-to-cost ratio. The values and magnitudes of ΔFE and benefit-to-cost are not exact here (due in part to the brevity of this 'quick look' study) but should be regarded as rough approximations. If a potential technological (or other) solution had a low benefit-to-cost ratio, then it was not included in the list. Finally, it should be noted that the ΔFE metric here is likely NOT additive if multiple solutions are implemented.

[b] While utilizing alternative fuels may not directly impact the fuel efficiency of a given vehicle to any significant extent, this fuel efficiency study views the development of alternatives to crude-oil-based fuels to be of critical importance to the Air Force, since these fuels can be produced domestically and are therefore a relatively secure supply. Hence the present study did explore, in a limited way, potential alternative fuels that could be used in air vehicles in particular. In this table, the ΔFE parameter should be viewed to be notional (and in fact may actually be zero or possibly even negative for a given fuel). The benefit in the benefit-to-cost ratio here derives from the potentially extraordinary benefits that would be associated with access to a more assured, domestically generated source of fuel.

SOURCE: Adapted from AFSAB (2006) and Karagozian (2006).

Finally, the AFSAB study considered the viability of alternative fuels to reduce dependency on foreign oil imports. With the exception of the use of Fischer-Tropsch synthetic fuel, the alternatives provided in this analysis do not meet near-term fuel efficiency improvement requirements.

SUMMARY

Table 1-2 illustrates that the subject of modifying engines and re-engining aircraft for various reasons has been studied extensively. However, two factors distinguish this study from the previous studies: (1) the selection of candidate systems herein is based mainly on their ability to reduce the Air Force fuel burden and (2) consideration is given to the entire fleet of large nonfighter aircraft. The following chapters analyze in depth the methodology for selecting the candidate systems for modifying engines and re-engining aircraft; additional factors that may reduce aircraft fuel consumption; promising alternative fuels and engine developments that may one day impact fuel consumption; and innovative contracting and financing approaches that the Air Force may employ with industry to reduce engine development and sustainment costs.

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2

Selection of Candidates

DETERMINING FACTORS

Based on the factors discussed in Chapter 1, the study identified four criteria for initially down-selecting certain large nonfighter aircraft from the full range of Air Force large nonfighter aircraft: (1) fleet size, (2) fuel consumption, (3) aircraft utilization rate, and (4) maintenance and support costs. In addition, the committee considered (5) the fuel efficiency improvement that is plausible for a given aircraft type and (6) additional operational benefits that could result from re-engining. Each criterion is described in more detail below.

Fleet Size

It is generally much easier to make the case that a proposed modification is worth the cost when sufficiently large inventories of a particular mission-design-series (MDS) designator—as an example, for the C-130H aircraft, the mission is C (cargo), the design is 130, and the series is H—are available to defray the nonrecurring research, development, testing, and evaluation costs. There are some noteworthy exceptions. In some cases, a particular modification might be applicable to several MDSs, so that a modification that appears very unattractive when evaluated for a single MDS with only a few airplanes might look considerably more attractive when all applicable MDSs are grouped together. In other cases—for example, the Joint Surveillance and Target Attack Radar System (JSTARS)—the operational benefits and potential cost savings from reduced maintenance and spares might make a compelling case, even for a small number of aircraft, that quite overshadows the benefits of the fuel savings. Nevertheless, number of aircraft in the inventory was a very strong factor, in both the first-order analysis used to focus committee efforts on a reduced number of MDSs and then on the return on investment (ROI) calculations performed on the subset.

Length of Service in Inventory

The length of the payback period over which the initial investment is spread clearly has a large impact on the attractiveness of a proposed modification. If the payback period is very short, say 5 years, very few modifications would make the cut if the only considerations were economic. If the payback period is long, measures providing only modest cost savings—say, through fuel savings—can become economically attractive. Unfortunately, the length of time a particular MDS will remain in the inventory from today is not predictable with much confidence.

The Air Force has a planned retirement schedule for all MDSs based on a number of important factors, only one of which is the estimated airframe life in hours. Other factors include such things as the vintage of the component technology, which affects reliability, the availability of spares, the viability of the vendor base, and other factors that in turn affect not only the estimates of future support costs but also, in some cases, the operational suitability of the aircraft for modern conflict. Aircraft of the class examined by this study typically have long airframe lives, about 30,000-50,000 hours. Considering that a typical utilization rate for these aircraft might be ~500 hours per year, they could be around for 60 to 100 years, if and only if estimated airframe life were the only consideration, which it is not. The other considerations typically lead to the much earlier planned retirement of a particular MDS. These plans become very volatile, however, as budgetary pressures preclude replacement of the MDS with more modern airframes.

Table 2-1 shows the inventory of various MDSs and illustrates the above points by estimating the remaining life assuming 30,000 hours airframe life for those aircraft with very stressful missions and

TABLE 2-1 Inventory and Estimated Retirement Dates Based on Assumed Airframe Lives and Flight Hours Shown

Aircraft Type	Total Active Inventory	Annual Flight Time for an Aircraft (hr)	Assumed Service Life (hr)	Remaining Life (hr)		Estimated Year of Retirement[a]	
				Minimum	Maximum	Start	Complete
B-1B	65	273	30,000	23,072	27,007	2089	2103
B-2A	21	275	30,000	25,088	28,378	2095	2107
B-52H	76	316	30,000	8,964	17,080	2032	2058
C-130E	151	502	30,000	–5,727	14,604	1993	2033
C-130E other variants	16	483	30,000	–4,737	11,757	1994	2028
C-130H	272	433	30,000	9,219	27,221	2025	2067
C-130H other variants	130	428	30,000	8,016	26,574	2023	2066
C-130J	37	352	30,000	27,475	29,970	2082	2089
C-130J other variants	16	246	30,000	27,659	29,916	2116	2125
C-135 other variants	32	414	40,000	–7,608	26,007	1986	2067
C-17A	154	1108	40,000	28,247	39,947	2030	2040
C-5A/B/C	111	367	40,000	16,194	26,819	2048	2077
E-3B/C	32	537	40,000	16,886	22,575	2035	2046
E-4B	4	309	40,000	26,219	28,077	2089	2095
E-8C	19	512	40,000	Refurbished[b]	Refurbished[b]	2035	2045
KC-10A	59	783	40,000	18,607	25,701	2028	2037
KC-135D/E[c]	115/65	306	40,000	13,338	23,907	2048	2082
KC-135R/T	420	366	40,000	9,460	26,963	2030	2078
Other	151	538	40,000	23,850	39,922	2048	2078

[a] Illustrative start retirement date is [2004 + (assumed service life – minimum time remaining (hr))/annual flight time per aircraft], where 2004 is the year the data in the table were collected. The illustrative end retirement date is similar but substitutes maximum time remaining.

[b] While the Boeing 707 was near the end of its commercial life when purchased by the Air Force, the refurbishment was so extensive it might be reclassified as a remanufactured aircraft when put into Air Force service.

[c] The Air Force is currently withdrawing the KC-135D/E from the active inventory. Of the 115 total aircraft, 65 KC-135D/E are carried in the active inventory in 2006.

SOURCE: United States Air Force, Program Data System database.

40,000 hours for all others. Some of the C-130E and C-135 variants have already exceeded the assumed airframe life (remaining life is negative; these are shaded in the table). These MDSs are now being retired, along with the KC-135E. The remaining aircraft have substantial airframe life remaining.

The committee dealt with this uncertainty in two ways corresponding to the needs of the study at two different points:

- The initial stage, where the entire ensemble of large nonfighter aircraft was reduced to the smaller set to be examined in detail. In this case, the only MDSs that were eliminated were already being taken out of the inventory, mainly because they were approaching the end of their service life for other reasons as noted above (C-130E, KC-135E).
- The more detailed evaluation of the smaller set of MDSs. At this point, the ROIs were calculated such that the discounted cash flows were based on a continuous timeline so that any particular criterion for payback could be easily considered (planned retirements, airframe life, congressionally mandated payback period of 25 years.)

Fuel Consumption Rate

The usual practice in figuring fuel consumption, particularly when a new system is acquired, is to specify a spectrum of mission profiles and meticulously calculate the fuel consumption rate averaged over that spectrum. For new system acquisition, there is little alternative to this procedure since there is no experience base for aircraft that do not exist yet. For all aircraft under consideration in this study, the committee has a very substantial experience base from which the fuel consumption rates (pounds or gallons per hour) may be derived. These fuel consumption rates are the average over the mix of mission profiles actually experienced. The general principle the committee followed is that these average fuel consumption rates represent the best information available absent compelling evidence to the contrary. The only compelling evidence found by the committee that required special consideration was associated with the cases where engine enhancements allowed reaching altitude sooner and higher cruise altitudes, both of which would presumably be exploited if the capability were available. The incremental fuel savings were estimated for these cases.

Aircraft Utilization Rate

To make a business case for action that attempts to save fuel, one must know how many hours an aircraft might expect to fly in a year. The higher the use rate, the easier it is to make a good business case for even small improvements in fuel efficiency. In evaluating Air Force aircraft, it is very important to realize just how low the use rate is for these aircraft, how different it is from commercial practice. Whereas a commercial airliner might fly 3,000 to 4,000 hours per year, an Air Force aircraft of similar size might fly 300 to 900 hours per year, 5 to 10 times less.

The reason for the striking difference is very straightforward. In commercial practice, an idle airplane means lost revenue and zero ROI. In contrast, the military must prepare for war and hope that it never comes. This means that the military must be equipped with the right kinds and numbers of equipment to prevail in wartime, yet good stewardship demands that in peacetime, the equipment be used just enough to maintain an adequate level of training for personnel.

This 5- to 10-fold difference between military and commercial practice explains why, absent considerations of force structure and alternative innovative approaches to financing, it is so much more difficult to make a good business case for large, expensive modifications of Air Force aircraft. The primary consideration is money saved as a result of a modification that decreases fuel consumption.

Maintenance and Support Costs

Total engine repair cost includes four operating and support (O&S) cost elements: maintenance personnel, consumables, depot-level reparables (DLRs), and engine overhaul. The Cost Analysis Improvement Group (CAIG) of the Office of the Secretary of Defense (OSD) defines the elements as follows:

- The maintenance personnel cost element reflects the pay and allowances of military and civilian personnel who support and perform maintenance on the engine. Depending on the maintenance concept and organizational structure, this element will include maintenance personnel at the organizational level and possibly the intermediate level.
- Consumables are materials and bits-and-pieces repair parts that are used up, or consumed, during maintenance.
- A DLR is the unit-level cost of reimbursing the stock fund for purchases of DLR spares (also referred to as exchangeables) used to replace initial stocks. DLRs may include repairable individual parts, assemblies, or subassemblies that are required on a recurring basis for the repair of major end items of equipment.
- Engine overhaul is typically the most complex work and requires expertise or equipment not available at the organizational or intermediate levels.

Figure 2-1 breaks down the Air Force's total aircraft O&S costs first into total engine O&S costs and then by the cost elements described above. As can be seen, the cost of engine O&S in FY05 was about 20 percent of total aircraft O&S costs.

Figure 2-2 shows engine O&S costs trends since 1999 for all Air Force nonfighter aircraft. Interestingly, the overall cost has declined since 2003.

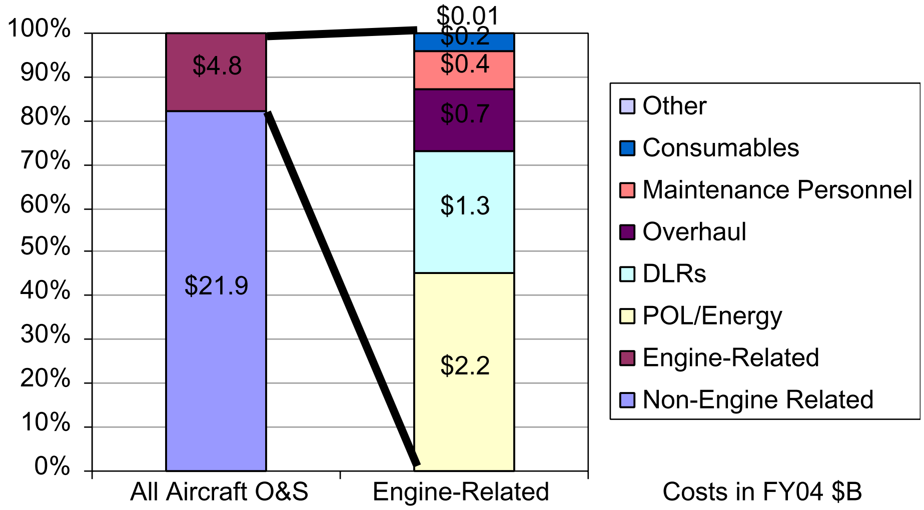

FIGURE 2-1 Total aircraft O&S costs and engine-related costs in FY05. POL, petroleum, oil, lubricants. SOURCE: AFTOC (2006).

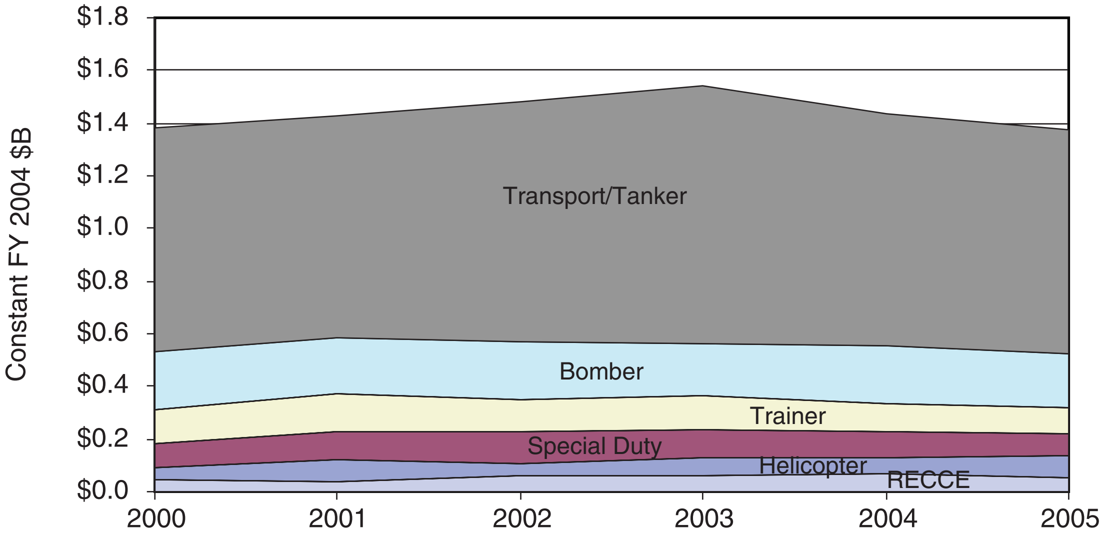

FIGURE 2-2 Air Force nonfighter engine O&S costs. SOURCE: AFTOC (2006).

Plausibility of Significant Improvements

As is to be expected in any business case, the total cost (how much you spend), the prorated benefits (how much you get back each hour of operation), and the remaining operational life (number of hours for which you can reap the benefits) are the key factors that determine whether to re-engine an airframe. With this in mind, it is important to understand the range of values that these parameters can take on, and thereby understand why certain re-engining programs are viable while others are not.

The cost to re-engine an aircraft can vary significantly. If there is a commercial engine that can fit within the housing of the existing engine with only minor modifications, the per-engine cost will be close to that of the engine itself. If significant aerodynamic, electrical, hydraulic, and structural modifications are required, and/or a totally new engine is required, the cost can be very high.

The benefits can also vary significantly, depending on the type of re-engining program that is conducted. For example, a relatively inexpensive re-engining program might provide only modest benefits, while a more expensive program might provide more significant benefits. Thus, depending on the cost/benefit relationship, the best option might be a more expensive option.

The benefits might also be limited by the constraints of the mission. For example, a low-observable aircraft might not be able to accept a certain engine even though the engine would consume much less fuel, because the higher exhaust temperature or larger cross-section would compromise its observables.

The time over which the cost to re-engine can be recovered is the third key factor in determining the net benefit of a new engine. For example, if an aircraft is near the end of its operational life, the benefits would have to be dramatic to be able to recover the costs before the airframe is retired; even in this case, however, the engines might have significant residual value, which could affect the outcome of the cost/benefit analysis.

Even though this is a constrained optimization problem requiring in-depth analysis of the manufacture, installation, and operation of all the components, a first-principles analysis based on the results of previous in-depth studies and data made available to the committee, such as will be described later, provides ample basis for excluding certain aircraft from consideration. For example, a full-scale re-engining program for the C-17 would require changes to the airframe (aerodynamic and structural) that outweigh the modest improvements in performance that could be achieved given the relatively modern high-bypass engine. However, an engine model derivative program (EMDP), wherein components of the existing engine are improved as new technology that can be retrofitted becomes available, could be a cost-effective means of achieving improvements at low to moderate cost. Similarly, any new engine for the B-2 would need to meet all the low-observable requirements for the aircraft. The only engines that have inherently low-observable characteristics incorporated into the front and back frames that would meet or exceed the radar cross section (RCS) requirements are the F119, F135, and F136. Given the constraints of the mission and the number of aircraft to be considered, a B-2 re-engine option would therefore seem to be too expensive and was eliminated from consideration in this study.

Treatment of Additional Operational Benefits

Lower fuel consumption is not the only benefit of new engines. The introduction of new engines to an existing airframe can result in improved operation capabilities that are just as valuable to the Air Force. For example, in a press release dated July 7, 2006, regarding the re-engining program for the C-5 (GE Aviation, 2006), GE says “The CF6-80C2 will provide the C-5M with a 22 percent increase in thrust, a 30 percent shorter takeoff roll, 58 percent faster climb rate and will allow significantly more cargo to be carried over longer distances.”

Lower fuel consumption and operating and maintenance costs and higher aircraft availability can easily be valued in terms of dollars and cents. For example, one might assume that each percentage point reduction in the fuel consumption of an aircraft will result in an equal percentage point reduction in the total fuel bill for that aircraft, and each extra hour that an aircraft can be operated between maintenance events reduces the cost of maintenance. On the other hand, such a valuation would be conservative as it does not consider the potential for reducing the number of aircraft and the number of people required to conduct the missions. If this type of follow-on savings were taken into consideration, the business case for re-engining would certainly look more promising. Nevertheless, such considerations as rebalancing the force structure among the major elements (fighters, tankers, intertheater airlift, etc.) are well beyond the charter of the committee and would require a significant effort that the Air Force undertakes as a matter of course. The greater capabilities of the force elements considered in this report should be an input to those efforts.

LIST OF CANDIDATE AIRCRAFT AND METHODOLOGY FOR SELECTION

One of the first tasks faced by the committee was to establish a methodology for selecting which aircraft and engines it would analyze. Although the Air Force is a significant consumer of petroleum products, on a national scale it is relatively unimportant, accounting for only 1.0 percent of the total U.S. demand in the most recent year for which data are available (2005). Thus, if major savings in fuel consumption are to be achieved, only those aircraft that are large consumers of fuel need to be considered.

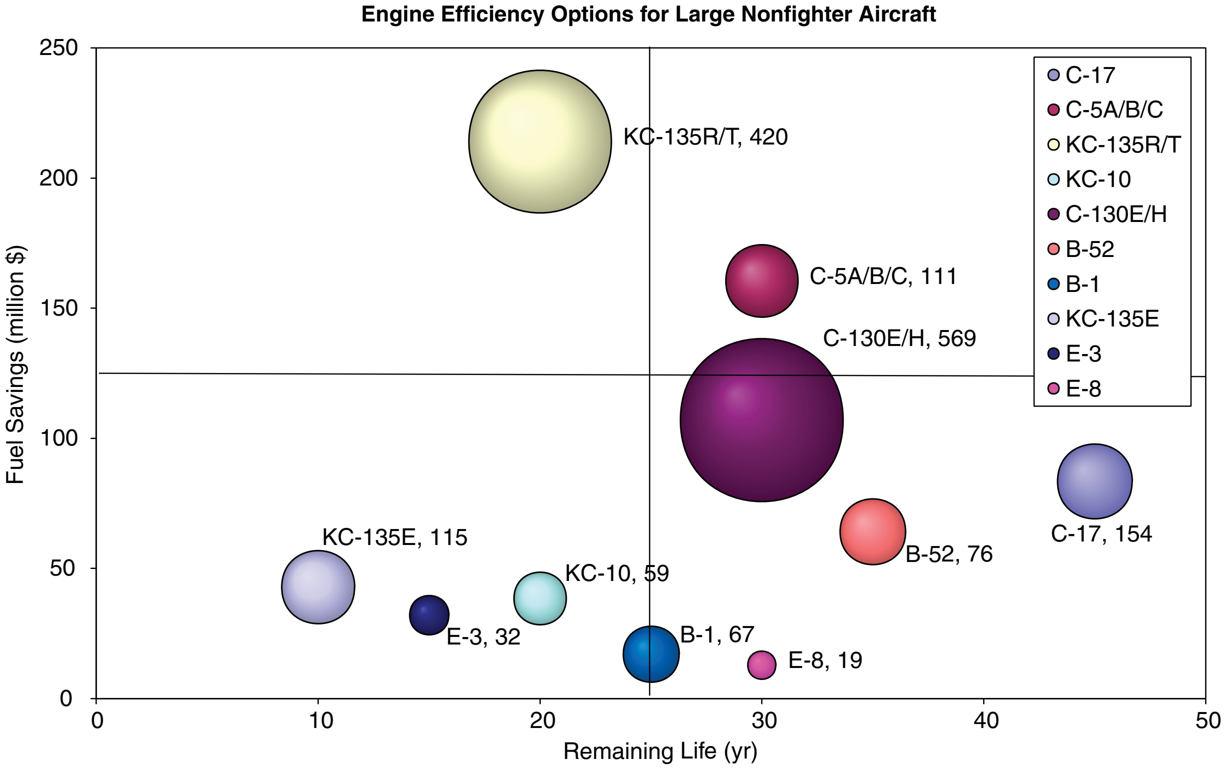

FIGURE 2-3 Potential fuel savings by aircraft type (based on a fuel price of \$2.14 per gallon). SOURCE: Committee generated.

From a list of candidate aircraft provided by the Air Force and arranged in order of quantity of fuel consumed, the first step was to weed out some of them. Accordingly, the following considerations were applied to the lists to achieve down-selection to 10 aircraft types:

1. Aircraft such as the C-17, which has relatively modern engines that are not likely to realize major improvements in fuel economy, were not studied in any detail.
2. Aircraft with common engines (such as the TF33) were treated as a group.
3. The most attention was paid to the groups of aircraft with the largest total fuel consumption.
4. Aircraft such as the C5-A/B, which have already been selected for re-engine programs, were included in the study but not analyzed in depth.

As a first cut, a plot was constructed that mapped potential fuel savings (based on 2005 fuel consumption as reported in AFTOC, 2006) for each group of aircraft against the remaining life, as provided by the Air Force. This plot is shown in Figure 2-3. The diameters of the bubbles are proportional to the number of that type of aircraft in the Air Force fleet. Also, the aircraft of greatest interest are those that lie closest to the upper right-hand corner of the plot.

The committee also believed there might be other reasons for including a particular aircraft in the study, such as serious performance or operational issues (in the case of the E-8, for example) or serious reliability and maintainability issues.

TABLE 2-2 Candidates for Further Analysis

MDS Designator	Re-engining	Engine Modifications	Aerodynamics Modifications
C-130H	X	X	X
B-1	X	X	
KC-135R/T		X	X
C-5	X		
KC-10		X	
E-3[a]	X		X
E-8[a]	X		X
KC-135D/E[a]	X		X
B-52[a]	X		

[a] These aircraft should be considered as a group with a view toward eliminating TF33 from the Air Force engine inventory.

SUMMARY CANDIDATES FOR STUDY

The analysis to this point, combined with the engineering judgments of the committee members about the plausibility of achieving significant improvement, allowed selecting the aircraft shown in Table 2-2 for more detailed consideration and further analysis in the remainder of the report.

REFERENCES

AFTOC. 2006. Aircraft usage and fuel consumption. Air Force Total Ownership Cost Database. May 15.

General Electric Aviation. 2006. CF6 engines power historic first flight of Lockheed Martin C-5M Super Galaxy. Press release. Cincinnati, Ohio: General Electric Aviation. July 7. Available online at http://www.asd-network.com/press_detail_B.asp?ID=8500.

Miller, B., and J.-P. Clarke. 2005. Real options and strategic guidance in the development of new aircraft programs. 9th International Conference on Real Options. Paris, France, June 22-25.

3

Proposed Engine Modifications and Re-engining

The committee has looked at a number of potential engine modifications as well as concepts for re-engining of current aircraft. In general, at 2006 fuel prices, it was difficult to recommend any modifications or engine changes on the basis of fuel savings alone. Some changes, however, bring significant operational improvements and maintenance benefits and should be considered by the Air Force.

KC-135 R/T AIRCRAFT

Among the options available for reducing the weapons system fuel consumption are the following:

- Changing the mission,
- Reducing aircraft drag,
- Upgrading the propulsion system,
- Modifying the aerodynamics, and
- Modifying the operational and maintenance practices.

From the above list of options, upgrades to the propulsion system were considered the most cost-effective approach for the KC-135 R/T fleet. There are currently 420 KC-135 R/T in the Air Force inventory. They are powered by 1,799 F108/CFM56-2 engines (1,744 installed and 55 spare). The fleet averages 400+ hours per year per aircraft. For planning purposes it can be assumed that they fly 500 hours per year. The fuel consumption of the KC-135 R/T fleet accounts for a significant share of the Air Force mobility fleet needs (Figure 3-1).

The F108 engine also makes up a significant portion of the mobility fleet inventory (Figure 3-2). The question before the panel is: Should the modification of F108 to gain improved fuel burn be considered at this time?

Engine modifications have been applied to the CFM56 fleet through the years. The latest modification is the three-dimensional (3D) Aero modification program, which has been introduced on the commercial side (CFM56-2), and the service life extension program (SLEP), which has been introduced on the F110-powered fleet. The 3D Aero program and SLEP are similar modifications of the core engine

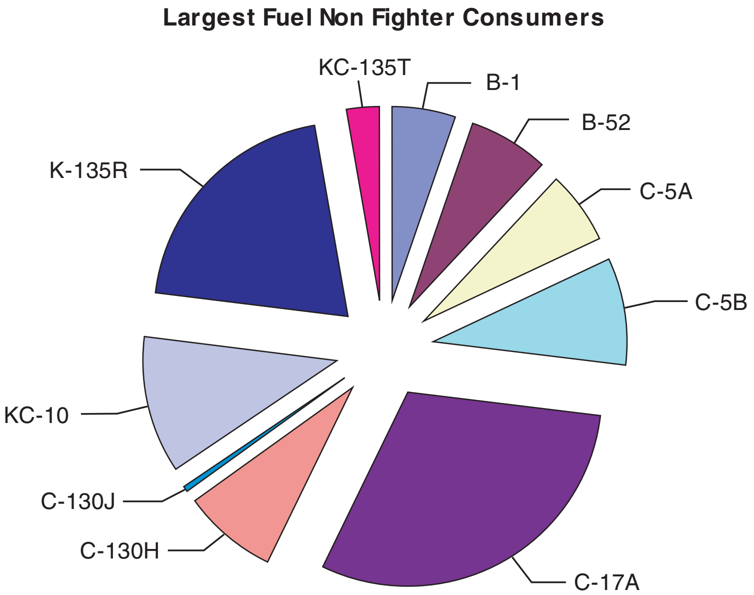

FIGURE 3-1 Number of aircraft in the Air Force large nonfighter aircraft inventory. SOURCE: DESC (2005).

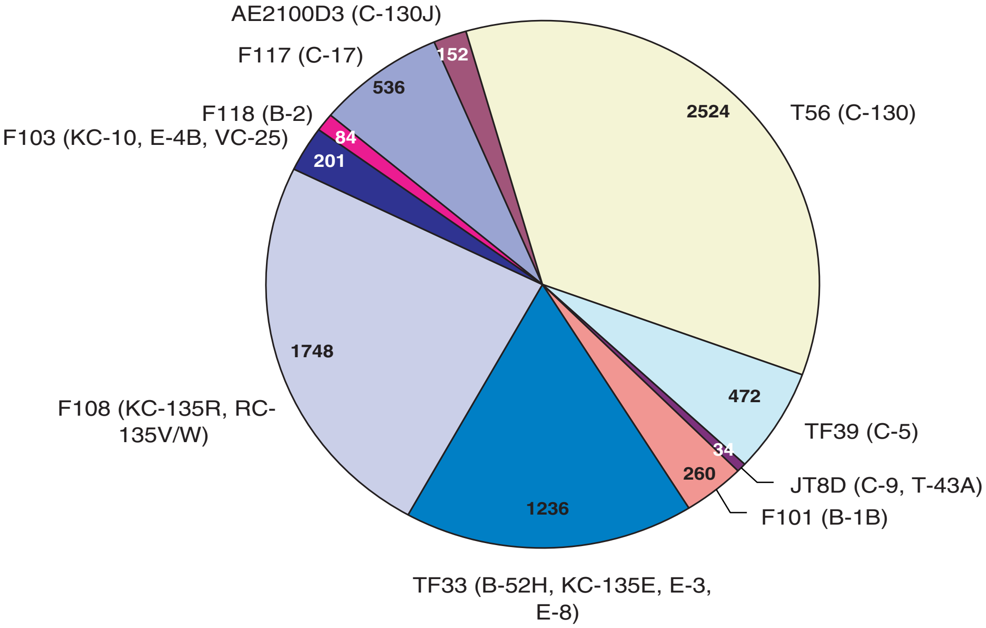

FIGURE 3-2 Number of engines installed in the Air Force large nonfighter aircraft fleet. SOURCE: Amos (2006).

with a new version of compressor blades, a modified combustor, and modified high-pressure turbine vanes and blades to improve the aerodynamics.

An engine upgrade has been proposed that involves turbomachinery modifications. This upgrade should yield 2 percent specific fuel consumption (SFC)/fuel burn improvements (see Figure 3-3).

The projected improvement is based on data from the incorporation of similar modifications to the F110 engine family. The projected cost for the modifications is $15 million for nonrecurring engine tooling. No nonrecurring work is anticipated for the airframe. A number of upgrades have been and are being introduced in the commercial CFM56 engines. Examples are 3D and tech insertion programs, both of which result in fuel savings and increased reliability. They should be considered by the Air Force for potential upgrade to the F108-powered fleet.

The modifications can be incorporated during a shop visit or while the aircraft is in depot for other maintenance reasons. The additional rewiring cost per shop visit is projected to be $1 million. The time interval from program go-ahead to delivery of the first aircraft is estimated at 24 months. The modifications are predicted to reduce maintenance costs by 25 percent for a projected time on wing of 12,000 engine flight hours. Projected fuel savings per airplane vary, from $35,000 per aircraft per year to $81,000 per aircraft per year given fuel costs of $2.14/gal and $5.00/gal, respectively. In addition, slight time on station and range improvement benefits are expected. The KC-135 fleet fuel consumption represents a significant part of the Air Force fuel usage for transport, tanker, and bomber aircraft. The decision to proceed with this modification hinges on weapons system service life considerations, the fuel cost impact, the potential residual value of upgraded engines, and the relative importance of reducing U.S. dependency on foreign oil.

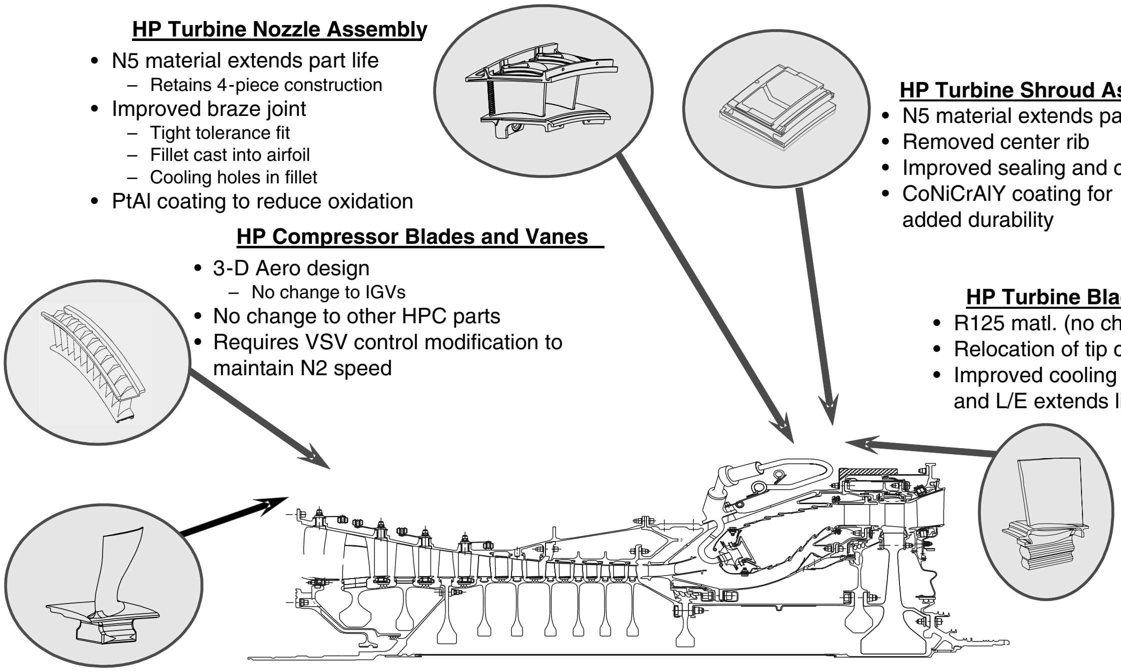

FIGURE 3-3 Details of proposed upgrades for the CFM56 engine. IGV, inlet guide vane; HPC, high-pressure compressor; VSV, variable stator vane; L/E, leading edge. SOURCE: CFM International.

TABLE 3-1 Comparison of Candidate Engine Characteristics[a]

		Specific Fuel Consumption		Dimensions (in.)		
Engine Model	Horsepower	SLTO[b]	ALT[c]	Diameter	Length	Weight (lb)
T56-A15	4,591	0.540	0.383[d]	44.6	146.3	1,848
T56-S3.5[e]	4,591	0.500	0.366[d]	44.6	146.3	1,894
T56-A427	5,823	0.470	0.356	48.3	146.3	1,940
AE 2100	4,591	0.460	0.342[d]	33.6	124.0	1,644
PW150	5,071	0.433	0.350	30.2	95.4	1,583

[a] *Aviation Week and Space Technology Source Book 2006*; pp. 142 and 145.

[b] Horsepower SFC – lb/HP hr; SLTO, Sea Level Take Off, references standard takeoff conditions. Standard for rating an aircraft engine.

[c] Thrust SFC lb/lb-hr at 12,000 ft, 220 kt. ALT, Altitude.

[d] Values corrected after release of the January 31, 2007, prepublication version of the report.

[e] Estimate based on Egbert and York (2006).

C-130 AIRCRAFT

The C-130 fleet is one of the largest currently in U.S. military operations, with over 500 aircraft in the Air Force inventory, and the various models of the Rolls-Royce T56 engines that power the aircraft account for the largest share of engine types in the inventory. Of these aircraft, approximately 250 are H models and have life expectancies beyond the year 2020. The other earlier models do not have adequate service life to be good candidates for re-engining (O'Banion, 2006). In addition, approximately 40 C-130J models are derivatives of the H model and incorporate significant upgrades to the flight decks, engines, and other parts.

Because the C-130 aircraft is so ubiquitous and versatile and has such a high utilization rate, it accounts for approximately 10 percent of the total Air Force fuel consumption and has been the subject of many engine upgrade studies and activities. The latest T56 engine model fitted to the aircraft, the T56-A15, is designated Series III. Another example of continuous improvement was a focused propulsion study that resulted in flight test and demonstration on the C-130 of the T56-A100, which was the product of the Air Force Engine Model Derivative Program (EMDP) of the early 1980s. More recently, studies have been conducted for the Special Operations Forces program office, Propulsion Development Systems Office's Advanced Projects Division (Aeronautical Systems Center/Special Operations Forces (ASC/LU)), addressing improved performance for the gunship version of the aircraft and for both the airframe company and a number of engine companies. Some of the information provided from these studies is included in Appendix G. The C-130J derivative concept aircraft has as its centerpiece a new engine (the AE 2100) and propeller.

There are five engine candidates that are available from other military or civil applications or that might be considered only slightly modified derivatives of existing engines and that would therefore require only low levels of qualification testing prior to fleet introduction.[1] These are shown in Table 3-1: (1) an evolutionary derivative of the current Series III engine incorporating some features from the

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[1] The GE38 was not included in this review since it was considered to be in an early development stage and not readily available.

EMDP, (2) Rolls-Royce engine T56-S3.5, (3) the T56-A427, the current production engine, used on the latest version of the Navy E-2C aircraft, (4) the AE 2100, used on the C-130J, and (5) the Pratt & Whitney Canada PW150, used on a civil turboprop. This table combines information from a public domain source (*Aviation Week*), from a Rolls-Royce briefing to the committee referenced in the table, and from calculations by the committee and is provided here for general reference.

The improved engines benefit the fleet in terms of life-cycle costs in the areas of savings on fuel consumption and maintenance. The estimated costs of fuel are provided in Table 3-2 at two fuel prices. The projected improvements in maintenance actions are shown in Table 3-3. Carrying these through to estimated cost savings is not included here since the related costs involve reductions in operational and depot personnel and is considered beyond the capability of the committee.

The introduction of new engines and props provides the opportunity for the C-130H fleet to be moved to modern maintenance and support programs, including active systems to monitor real-time conditions and components and accessories designed to meet contemporary reliability expectations. These result in significant improvements in parameters associated with safety, including the in-flight shutdown rate and the mission abort rate. The modern engines and propellers also provide significant improvements in environmental impacts in the form of noise and emissions. For example, the 70 dBA noise footprint of an aircraft fitted with modern engines and props is reduced from 24.25 to 5.4 square miles. These propulsion changes also offer significant improvements in aircraft operational characteristics—for instance, the length of the landing field can be reduced from 4,000 to 3,100 feet and the cruise altitude increased from 18,000 to more than 22,000 feet for one popular configuration. These improvements can positively impact the aircraft and fleet mix and applications.

The first-order financial components of retrofit development, hardware acquisition, and fuel savings are shown in Table 3-4. Note that some of the engine costs were supplied by the contractors and have not been subjected to the rigorous verification of normal procurement practices.

TABLE 3-2 Fuel Usage and Costs[a]

	T56-A15	T56-S3.5	T56-A427	AE 2100	PW150
Annual fuel use (million gal)[b]	171	157	149	123	129
Annual fleet fuel cost (million $)					
Fuel at $2.50/gal	428	393	373	308	323
Fuel at $5.00/gal	855	785	745	615	645

[a] Based on contractor data and estimates.

[b] Egbert and York (2006).

TABLE 3-3 Propulsion System Reliability and Maintenance Actions

	T56-A15	T56-S3.5	T56-A427	AE 2100	PW150
Reliability in terms of MTBR per hour[a]	1,274	NA	1,500	3,500	4,300
Maintenance actions per hour of flight time × 100 (%)[b]	100	60	60	50	50

NOTE: MTBR, mean time between repairs.

[a] Based on contractor data and calculations.

[b] Egbert and York (2006).

TABLE 3-4 Components of Financial Evaluation[a]

Costs	T56/S3.5	T56/A427	AE 2100	PW150
Engine costs	0.433	0.753	1.0	0.965
Propeller costs (million $)	0.225	0.225	0.250	0.250
Nonrecurring costs of the re-engining (thousand $)	50	17	30	70
Nonrecurring costs of modifying the airframe (thousand $)	10	15	15	25[b]
Annual fuel savings (%)[c]	8	13	28	25[d]

[a] Engine costs for the AE 2100 were provided from an average of contractor-provided data; costs for the other engines were calculated using the percentages in Egbert and York (2006). They are expressed here in relative terms to avoid the use of proprietary data; other costs and the fuel savings are from Egbert and York (2006) or other contractor data.

[b] Committee estimate.

[c] Annual fuel savings compared to baseline engine (T56-A15).

[d] Value corrected after release of the January 31, 2007, prepublication version of the report.

These benefits are sensitive to nonrecurring costs and future fuel costs and require detailed analysis beyond the scope of a study such as this. However, the payback period was shown to be within the structural life of the C-130H fleet and its projected active use within the force structure. The nonrecurring cost of the re-engining varied somewhat from study to study, probably because of the varying extent to which ancillary features such as advanced next generation propellers and other features from the C-130J were incorporated into the airframe and propulsion system at the time of the re-engining.

The referenced reports found in Appendix C, along with a report focused on Special Operations aircraft, demonstrate that re-engined aircraft have a variety of attributes that can be applied in different ways to accomplish a range of Air Force missions. The fuel savings for the aircraft with new engines vary from 12 percent to 28 percent, depending on what proportion of a more efficient engine's capabilities is used to enhance the performance of the aircraft and what proportion of its efficiency is used to duplicate the existing mission profiles and conserve fuel. These prior studies also highlight the extent to which the improved aircraft performance is used to displace existing aircraft by fully utilizing the increased capability of the reconfigured aircraft. These savings may come from fewer operational aircraft, smaller air crews, and reduced support operations. The quantification of these savings was beyond the purview of this report but should be considered in a comprehensive study of the subject.

The T56 engine is currently in use in the C-130, C-2, E-2C, and P3 aircraft by the U.S. military and by the militaries of many of its allies. The AE 2100 is in use in the C-130J aircraft and in the C-27J currently proposed for the Army medium airlift requirements. Both the AE 2100 and the PW150 are in use in civil airline fleets. In addition the AE 2100 core is the basis for the AE 1107 turboshaft engine that powers the V-22 Osprey and the AE 3007 turbofan that powers the Embraer family of regional jets, the Citation X business jet, and the Global Hawk military unmanned aircraft system.

These multiple applications provide the opportunity for existing commercial product support organizations to support aircraft re-engined with either the AE 2100 or the PW150. And in the case of the AE 2100 there are currently support contracts in place to provide maintenance for the Marine V-22 and C-130J engines and the Air Force C-130J fleet (Plummer, 2006).

These contractor-supplied maintenance approaches need to be evaluated in the context of Air Force force structure and staffing plans and quantified in terms of cost savings in a more detailed study of C-130 re-engining. It has been noted that the Air Force and Navy are already cooperating on maintenance approaches for the AE 2100 engine, but any re-engining study of the C-130 should also examine the possibility of aircraft using the T56 engine—for example, the Navy's E2-C, C-2, and P3 fleets.

Finding 3-1. The C-130 fleet is one of the largest in the Air Force inventory. Owing to its ubiquity, its versatility of use, and high utilization rate, it accounts for a significant portion of Air Force fuel usage.

Finding 3-2. The C-130 has been the subject of a major upgrade that incorporates new engines and new technology in the flight deck, propellers, and systems and is entering the Air Force and Marine fleets as the C-130J.

Finding 3-3. There are four near-term candidates engines for improving the fuel efficiency of the C-130: (1) a T56 upgrade, (2) the T56-A427 from the Navy's E2-C, (3) the AE 2100 from the C-130J program, and (4) the PW150, a civil engine.

Finding 3-4. The studies conducted to date have been based on a range of nonrecurring cost depending on the non-engine-related upgrades that are included in the costs.

Finding 3-5. The C-130H fleet, consisting of approximately 270 aircraft, has a planned life through the year 2025 and is a candidate for retrofitting with more energy-efficient engines.

Finding 3-6. The older C-130E aircraft fleet, which comprises approximately 150 aircraft is not a good candidate for engine upgrade from a financial perspective since the aircraft would require expensive structural life extension programs.

Finding 3-7. Several of the candidate engines and propeller systems could provide for significant improvements in terms of positive environmental impact for the C-130H.

Finding 3-8. The services have implemented contractor maintenance and support programs for the C-130J AE 2100 engine (and the common core AE 1107 turboshaft from the V-22), and these provide a database for innovative support concepts.

Conclusion 3-1. Re-engining the C-130H fleet with derivatives of the existing T56 engine shows the best financial case in terms of payback time from fuel cost savings, but it saves the least fuel.

Conclusion 3-2. Re-engining the C-130H fleet with new engines such as the AE 2100 or the PW150 saves the most fuel and has a payback within the useful life of the airframe.

Recommendation 3-1. The Air Force should conduct a detailed technical and financial study of the C-130 fleet to select and validate a preferred re-engining plan with fuel savings as the primary figure of merit. The Air Force should generate an implementation plan for financially viable candidates.

Recommendation 3-2. The Air Force should conduct a study of C-130 airframe and operational techniques focused on fuel savings needs and generate an implementation plan for financially viable candidates.

> **Recommendation 3-3.** The Air Force should pursue re-engining the C-130H on a priority basis, since this aircraft is one of the largest users of fuel in the Air Force inventory. The Air Force should use a competitive bid procurement process to provide the background for a decision on the C-130H models between the AE 2100 and PW150 engine options, either of which would appear to be acceptable on a technical and performance basis, and it should review the economics of engine efficiency upgrades (engine modifications) to the older models with a shorter remaining service life.

B-1 AIRCRAFT

There are currently 67 B-1B bombers in the Air Force fleet plus 29 aircraft in mothballs. They fly approximately 275 hours per aircraft per year. The Air Force would like to improve fuel efficiency, mission flexibility, and altitude capability, which could increase the B1-B utilization rate. The increase in altitude capability is needed to minimize their vulnerability to surface-to-air missiles and to 57 mm and anti-aircraft artilleries; also, they need to be refueled at 20,000 feet or less, which could put both the B-1B and the refueling aircraft in harm's way. There is, in addition, a chronic low-pressure turbine failure problem associated with high-temperature operation, and this leads to high maintenance costs.

In 2002, Maj Gen Dan Leaf asked Boeing to find the best way to increase B-1B mission flexibility, specifically by increasing altitude capability (see Summary 9 in Appendix C). Boeing studied many aircraft modifications and subsystem upgrades and concluded that re-engining of the F119 was the best solution. It found that the original B-1A altitude and Mach 2.2 speed (which the B-1B structurally inherited) could be restored by increasing the specific thrust of the production F119 engines.

Modification

The committee identified one candidate for engine modification:

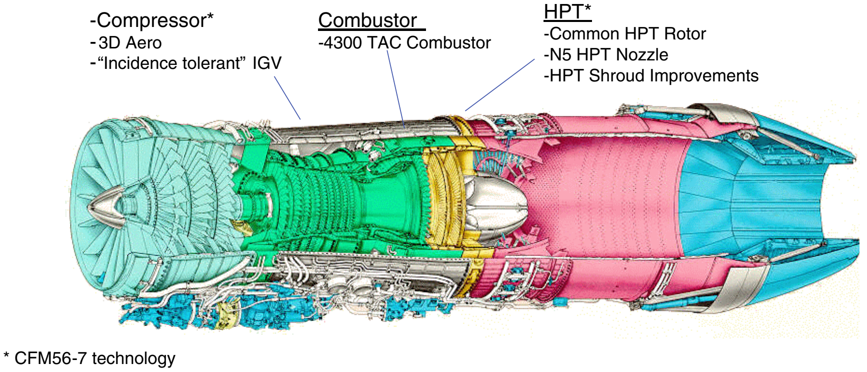
1. Modify the current F101 through a SLEP. This program would include a thrust increase, maximizing thrust at both midpower and augmentation, along with durability improvement incorporated in the low-pressure turbine. This would improve altitude capability by an additional 5,000 to 10,000 feet. There would be no specific fuel consumption benefits.

Figure 3-4 describes the existing F110 (engine used on F-16) SLEP. The F101 engine used by the B-1B uses the same core as the F110. The F101 SLEP would be similar to the F110 SLEP described in the figure.

Re-engining

The committee identified three re-engining candidates for the B-1B:

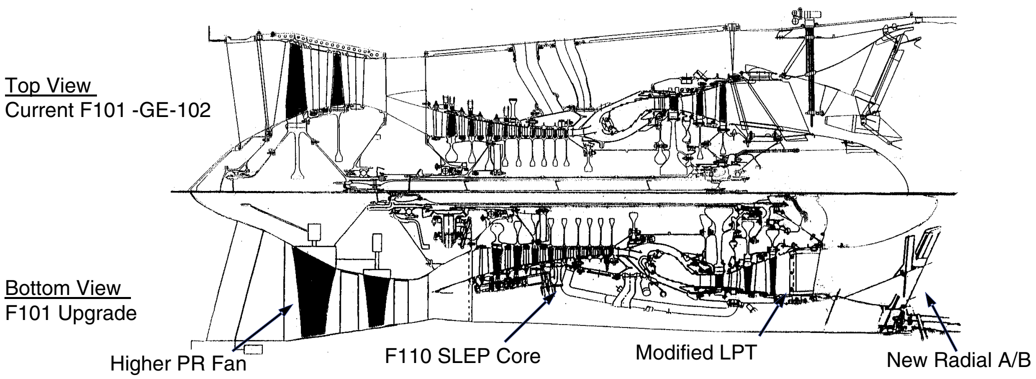
1. Proposed SFC upgrade of the F101 (see Figure 3-5), which would incorporate a new two-stage fan, a SLEP F101 core, a modified low-pressure turbine (LPT) new radial augmenter, and a new elliptical nozzle known as an augmented load-balanced exhaust nozzle (ALBEN) (see Figure 3-6), which has a 10 percent better SFC. The recurring cost is $500,000 per engine. An additional 3,000 foot altitude improvement is expected over the F101 engine modification SLEP. A 40 percent reduction in engine maintenance cost is projected with a time on the wing of 1,000 hours. The first aircraft delivery would occur 48 months after go-ahead. A fuel saving cost of $2.9 million per aircraft per year is anticipated.



F110 SLEP Benefits

- Address top safety drivers
- 2X increased time on wing
- Cost per engine flying hour decreased by 25%
- 66% decrease in inspection maintenance hours
- Reduces special inspections

FIGURE 3-4 F110 SLEP. SOURCE: General Electric.



Cycle Data Current/Proposed:

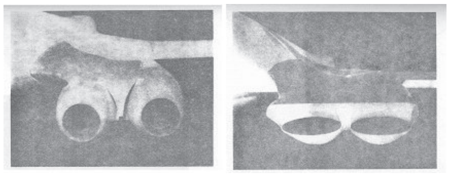
Wcor=360/370 pps; FPR=2.6/3.1; OPR=26/32; BPR=1.9/1.5 class

Proposed: Same T3, T41, T49 as F110 SLEP

		Sea Level		30k, Subsonic		35k Transonic, Dry					
Installed Performance*		Max A/B	Max Dry	0.8M Max Dry	0.95M Max Dry	0.8M Max Dry	0.95M Max Dry	1.1M Max Dry	1.2M Max Dry		0.8M/35K Max/Dry
F101 Upgrade vs Current	%DFnIN	+18%	+21%	+24%	+25%	+25%	+26%	+25%	+28%	%DSFC	+1%

FIGURE 3-5 Engine comparison of current versus proposed F101 upgrade. SOURCE: General Electric.

2. First, re-engine the B-1B with a production F119 engine (see Figure 3-7). The F119 engine provides survivability to eliminate the need for radar cross section vanes in the aircraft inlet. Then, optimize the robust F119 fan for improved spillage drag. Finally, integrate a new elliptical low-observable exhaust system (see Figure 3-8), which eliminates significant boat tail drag. Lift/drag improvements could allow the F119-powered B-1B to supercruise for sustained rapid response



B-1 Wind Tunnel Model Compared
Installed Performance of Axi Nozzle vs. ALBEN

Low drag nozzle developed for B -1A

- Wind tunnel data indicated potential for 5 -10% aircraft drag reduction
- Potential fix for aircraft acoustic fatigue

FIGURE 3-6 F101 Upgrade-ALBEN. SOURCE: General Electric.

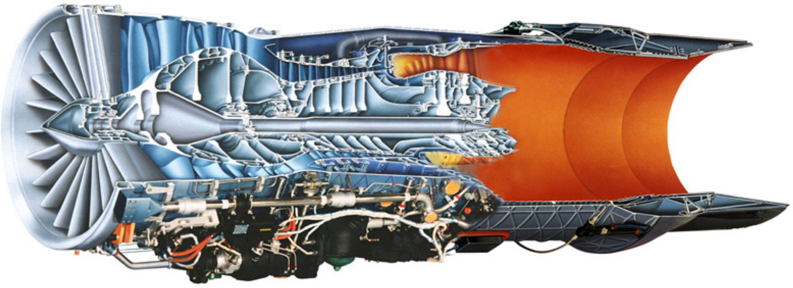


FIGURE 3-7 F119 cross section. SOURCE: Pratt & Whitney.

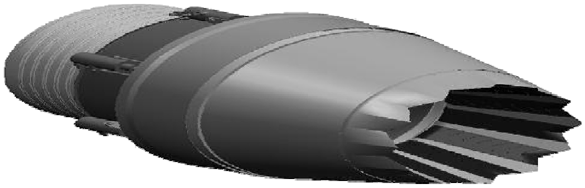


FIGURE 3-8 Elliptical nozzle. SOURCE: Pratt &Whitney.

ability. This system solution could provide the Air Force with Global Strike/Global Persistence attack and fighter/attack capability equivalent of seven F-18s in a Global Response Bomber size at a 50 percent improvement in propulsion system total cost of ownership. The F119 upgrade could be achieved for a nonrecurring engineering (NRE) cost (propulsion only) of $100 million.

3. Re-engining the B-1B with a derivative F119/F135 fan option could trade performance margin for improved fuel economy and enhance the total system impact to the B-1B range/persistence capability. This derivative configuration could be achieved for an NRE of $450 million.

Fuel Consumption

To fulfill the statement of task, which is to reduce fuel consumption for the B-1B, there are two alternatives:

1. EMDP for the F101, which includes a new fan and new nozzle to maximize fuel efficiency for the aircraft. This should decrease fuel consumption by 10 percent at NRE costs of $100 million.
2. An EMDP of the F119 engine, which would include a new fan and a low-observable elliptical nozzle to maximize fuel efficiency for the aircraft. This is estimated at an NRE cost (propulsion system only) of $450 million to $500 million each.

KC-10 AIRCRAFT

Background

The KC-10 aircraft is a derivative of the commercial DC-10, a 1970s vintage wide-body aircraft. The commercial version of this aircraft was powered primarily by the CF6-6 and CF6-50 engines; a few were produced with the Pratt & Whitney JT9 engine. The aircraft has been out of production for nearly 20 years.

The KC-10A fleet is equipped with GE F103 and GE F101 engines that were manufactured and certified to the same FAA standards as the CF6-50 commercial engines on DC-10 aircraft. These engines have served the industry and the Air Force well and have a reputation for reasonable maintainability, reliability, and fuel efficiency consistent with state of the art for second-generation, high-bypass-ratio turbofan engines of the era.

The KC-10 has one tail-mounted engine and two wing-mounted engines. The tail-mounted configuration is very engine specific. It is physically dimensioned to accommodate specific engines that were in production when it was being designed. It is likely that major redesign would be required for the installation of current state-of-the-art engines. In addition, many of the current engines were optimized for thrust production and may not provide significant fuel consumption benefits for the CF6-50.

Although the airframe structure and weapons system service life parameters could make it suitable for re-engining, the committee found no performance, operational, or cost-effectiveness justifications for such a program. Re-engining is driven basically by performance, availability, and cost requirements. Today, the KC-10 fleet meets all airframe requirements, and it is the committee's assessment that no change is warranted.

The CF6-50 engine was widely used on the DC-10, 747, and A300 aircraft. This relatively large commercial industry inventory of CF6-50 engines, parts, and maintenance capability acts as a reserve that can be drawn upon as needed to assure continued availability for the F103 engine.

Finally, there are no viable candidate engines that could improve fuel consumption by >10 percent or significantly reduce maintenance costs within reasonable cost/benefit parameters.

Technology Infusion Benefits

Propulsion system upgrade was considered as a potentially cost-effective approach for improved fuel consumption for the KC-10 fleet. There are currently 59 KC-10A aircraft in the Air Force inventory powered by 177 F103 engines. The Air Force retains 22 F103 engines in a spare capacity for the KC-10A fleet, with the equivalent of five more engines that are retained as modular spares.

High-Pressure Turbine Upgrades

The committee considered engine upgrades as a means to achieve fuel consumption and cost savings for the KC-10 fleet. The candidate upgrades were generated for commercial CF6-50 applications but have relevance for the F103 engine. The time, cost, and material content required to implement the upgrades is dependent on the configuration of the F103 engine to be modified. The committee determined that upgrades would not provide significant fuel consumption reductions. Upgrades do, however, offer reduced maintenance costs, improved exhaust gas temperature (EGT) retention, and the potential for improved residual asset value and reduced cost of ownership due to market value resulting from their commonality with commercial engine configurations.

A proposed upgrade for a high-pressure turbine (HPT) flow path would require an investment of about $200,000 per engine, with a projected savings of about $169 million by 2021 and a payback period of 6 years. The savings result from reduced material usage and lower maintenance costs.

Commonality Considerations for the Air Force Engine Fleet

Fleet commonality was reviewed to determine the potential advantages for reliability, maintainability, and/or performance derived from technology infusion. The E-4 is the only other aircraft in the Air Force stable of large aircraft powered by the F103 engine. No studies have been conducted, and no operational issues have been detected by the Air Force with respect to performance, availability, or operating cost limitations for the E-4 fleet.

Commonality Issues for the Commercial Engine Fleet

Since the F103 engine is the same as the commercial CF6-50 engine, the committee reviewed current activity within the commercial fleet to determine if benefits derived from such programs might have application in Air Force analyses for re-engining/modification.

A number of commercial operators are modifying their CF6-50 fleet with hot-section upgrade kits. The CF6-50 hot-section upgrade kit incorporates advanced HPT materials, coatings, and cooling technology from the latest generation of aircraft engine designs. This modification responds to operational experience, with the frequency of engine removals attributable to HPT components such as nozzles, shrouds, and blades. Incorporation of the hot-section modification results in predicted engine time on wing increasing as much as 25 percent. In addition, the modification provides improved EGT margin retention and a reduction in shop visits, scrap, and repair and material costs. Thus the upgrade kit is predicted to significantly improve engine life, cost of ownership, and long-term residual value for the commercial operator community.

The KC-10A fleet could realize minor fuel efficiency benefits, on the order of 0.33 percent, and a projected 15 percent reduction in maintenance costs through a CF6-50 upgrade/technology infusion program for the F103 engine in the form of hot-section modifications.

The estimated production rate for engine modification is about 30 engines per year. The payback period at this rate could not be justified solely on the basis of fuel savings. The projected 15 percent reduction in engine maintenance cost yields an annual savings for the KC-10A fleet, with an attendant payback period for any modification program.

Summary

There are no compelling operational performance, fuel consumption, availability, or operating cost issues to support a re-engine program for the KC-10A/F103 fleet. In addition, there are no candidate engines that could provide significant improvement in operational performance, fuel consumption, availability, or operating cost for the KC-10A fleet.

The projected fuel savings for the CF6-50 HPT/hot-section modification to the F103 engine for the KC-10A fleet do not meet the objectives of this study pertaining to the reduction in fuel consumption for the large aircraft fleet. However, the opportunity for reducing operating costs and improving mission performance/availability in the form of predicted improved on-wing time, improved EGT margin retention, reduced maintenance and material costs, and an attendant reduction in required maintenance manpower would justify review by appropriate Air Force weapons systems and process managers for these modifications depending on the priorities of these issues relative to overall weapons-systems management objectives.

> **Recommendation 3-4.** The Air Force should consider the hot-section modification a priority for the F103 engine to the extent Air Force weapons systems managers, planners, and policy makers consider that commonality with commercial engines has value with respect to maintenance (outsourcing, spares, parts, etc.), availability, improvement implications, and potential residual value.

> **Recommendation 3-5.** In general, where commercial engine/airframe counterparts exist (KC-10/DC-10, F103/CF6-50, KC-135/B-707, TF33/JT3, F108/CFM56, etc.), Air Force engine and weapons systems planners, managers, and policy makers should closely monitor the engine's original equipment manufacturers' (OEMs') and commercial operators' activities and actions relative to re-engining and engine modification as a measure of the cost/benefit for these activities.

C-17 AIRCRAFT

> **Finding 3-9.** The F117 is a modern, high-bypass, fuel-efficient engine on the C-17; however, it is the largest consumer of fuel in the Air Force's inventory of large nonfighter aircraft/engine systems.

> **Conclusion 3-3.** The F117 engine is a possible candidate for decreasing fuel burn by 1.1-1.7 percent. This could be accomplished by redesigning the high-pressure turbine and re-aeroing the low-pressure turbine. This assessment does not include benefits of integration, which has been shown to improve thrust-specific fuel consumption (TSFC) by 5-8 percent for other legacy systems. These elements include bleedless architecture through an electric vapor cycle, the environmental control system, better thermal management through fuel stabilization unit, and improved electrical power generation through a low spool generator.

> **Recommendation 3-6.** Since the C-17/F117 system is the largest consumer of fuel, the Air Force should conduct an engine model derivative program (EMDP) study with Boeing and Pratt & Whitney to determine possible fuel savings, implementation costs, and a schedule that would give the best return on investment for the Air Force.

For future planning purposes, the Air Force should track and request from Pratt & Whitney all changes to the commercial PW2037/2040 pertaining to reduced fuel burn and durability issues.

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4

TF33 Series Powered Aircraft

INTRODUCTION

The Air Force currently owns approximately 2,300 TF33 engines of various models that it uses on seven weapons systems, mainly the KC-135, E-3 Advanced Warning and Control Systems (AWACS), B-52, and E-8 (Joint Surveillance and Target Attack Radar System (JSTARS)) aircraft (Parker, 2006). Designed in the 1950s and manufactured in the 1960s and 1970s, the TF33 is one of the oldest engine families in the Air Force inventory. Given their age and number, TF33-powered aircraft have been the subject of numerous re-engining studies over the years (at least nine studies since 1984), one executed re-engining program (the conversion of most earlier KC-135s to the KC-135R model), and one in-progress program (re-engining of the E-8).

The re-engining of different TF33-equipped platforms is discussed in detail in the following subsections. However, there are four considerations that pertain to more than one platform and that may distinguish a present-day re-engining effort from past efforts. The first common consideration is that the maintenance interval of modern engines exceeds the life of these old airframes. Specifically, (1) the very long on-wing lives of the best modern commercial transport engines (7 years or more on wing, which amounts to 10,000 hr or more compared to the TF33's 1,500-2,500 hr), (2) the low annual utilization of most TF33-powered platforms (only 10-20 percent that of a commercial operator), and (3) the plans in 2006 for the inventory life of these platforms all combine to suggest that properly selected new engines would not be expected to come off the wing for an overhaul during the remaining life of the platform. Since major overhauls account for most of the maintenance cost associated with engine ownership, the true cost to the Air Force of these modern engines may be less than their cost based on a standard cost-of-ownership estimate, which spreads the overall maintenance cost over the total operating hours.

A second new consideration is the dramatic and rapid increase in the Air Force's overhaul cost for TF33 engines. Depot overhaul of a TF33 is estimated to have cost $257,000 in FY96. Since FY03, the TF33-PW-102 depot overhaul cost has increased by 300 percent, to $1.25 million per engine in FY06. This cost growth greatly surpassed the earlier 2 percent per year projections. The causes of this escalation were not made clear to the committee, but it notes that the commercial version of the TF33, the JT3D, which was once one of the largest engine fleets, has largely gone out of service since it does not meet environmental regulations of most of the developed world and is much less fuel efficient than current engines.

The third consideration is that with the exception of the B-52H, all of the other TF33-powered weapons systems are KC-135/B-707 variants or derivatives. Given that the KC-135Rs have been re-engined and the E-8 JSTARS re-engining is now in progress, a significant fraction of the nonrecurring engineering costs may be shared among platforms rather than duplicated.

The fourth consideration is that the Air Force maintains a significant engineering and overhaul capability to support its fleet of 2,300 relatively high maintenance TF33 engines. So long as a significant number of TF33s remain in the inventory, the Air Force must retain some overhaul capability. Should all of the TF33s be retired, however, then the $800 million inventory can be disposed of and the more than 188 personnel and 82,000 sq ft of support real estate can be suitably redeployed for other Air Force needs. For these nonnegligible savings to be fully realized, all TF33 engines have to be removed from the inventory. If, for example, all of the KC-135/B-707 variants are re-engined, this may strengthen the case for the B-52.

Taken together, these considerations strongly suggest that TF33-powered aircraft should be considered as a group rather than subjected to the traditional approach—i.e., airframe by airframe studies. In this case, the whole of the savings from re-engining all TF33 aircraft may considerably exceed the sum of re-engining the individual platform types.

The following sections discuss re-engining for each of the current platform types.

E-8 JSTARS WEAPONS SYSTEMS

Throughout the development history of JSTARS a number of engine options have been studied. By re-engining the JSTARS E-8C aircraft, the government will benefit from substantial reductions in fuel burn and other costs of ownership, while enhancing all operational requirements with a new installation that more than meets all environmental requirements.[1] However, in each case the conclusions were similar to those for the other platforms that had conducted business case analyses on payback—i.e., the payback period is too long to recoup the significant upfront nonrecurring engineering (NRE) and acquisition costs.

From its inception the JSTARS platform was structured around Boeing 707 aircraft that were being operated by the Air Force, foreign governments, and commercial carriers. The program utilized Boeing 707-320C (Air Force designation C-18) series aircraft obtained in the commercial marketplace as they were being phased out by the major and secondary commercial carriers. The 707-320C aircraft had received its Federal Aviation Administration (FAA) certification in April 1963. At the time the aircraft were procured from the used market, there were only limited engine options offered for them. The original Boeing 707-320 aircraft design goals were to provide an aircraft whose aeronautical performance was optimized for long-range flight, making it the first truly intercontinental jet aircraft. The Boeing 707 had adequate thrust to meet the needs of a commercial operator carrying large loads between distant points on the globe. The engines available for the aircraft back in the 1960s had 18,000 lb thrust in the JT3D-3 or -3B commercial configuration or 19,000 lb thrust in the -7 variant. It should be noted that the wing structure of a Boeing 707-320 series aircraft is nearly identical to the wing structure of an AWACS that is currently operating with a 21,000 lb thrust engine. However, the long radar aperture along the bottom fuselage of the aircraft results in problems with aircraft lateral stability, which is aggravated by increased

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[1] On January 18, 2007, the Air Force announced that it had selected the Pratt & Whitney (P&W) JT8D-219 engine to re-engine the entire Joint STARS fleet (Northrop Grumman, 2007).

thrust. Any re-engine program for the JSTARS aircraft will have to address the issue of improving the aircraft's lateral stability to meet military standards.

In the early 1990s, an early deployment of the two full-scale-development JSTARS aircraft during Operation Desert Storm demonstrated the operational effectiveness of the weapons system; however, a number of areas were identified that would need significant improvements in aeronautical performance to meet the original Operation Desert Storm requirements and to gain maximum utility from the E-8 system. The main areas identified were these:

- Reduced takeoff distances at maximum weight under military flight rules.
- Reduced time to achieve the JSTARS initial surveillance altitude.
- Larger engine oil tanks to extend aircraft time on station.
- Greater unrefueled range.
- Improved hot-day takeoff performance coupled with shorter runway lengths.
- Improved maneuvering capabilities at surveillance altitude.
- Reduced engine maintenance time between flight sorties.

The lessons learned from the Desert Storm deployment were assessed not just for the JSTARS surveillance role but also for related aircraft performance. A follow-on full-scale development (FOFSD) was proposed using the YE-8B aircraft, which was a derivative of the current Boeing/U.S. Navy E-6 aircraft powered with CFM56-2 engines. This engine develops 24,000 lb thrust and would have resolved a number of performance improvements sought by the operator. A primary consideration for any re-engining program for the JSTARS aircraft is the effect on radar performance. Unobstructed operation of the radar and improving the performance of the radar by increasing the operating altitude of the aircraft have been identified as two key considerations.

When affordability and availability of the Boeing YE-8B (new 707) became an issue owing to the cost of keeping the B 707 production line open, the program was rebaselined to again utilize a used 707-320 series platform. The ensuing FOFSD program used the same aircraft performance requirements as the FSD system. During the development phase for the FOFSD, an effort was made to resolve some of the aircraft's performance issues by offering to select used aircraft that were powered with the P&W JT3D-7 engine variant, which provided 5.5 percent more thrust than the FSD system. In addition, a study was done to determine if lower thrust JT3D-3B engines on an aircraft acquired for the program could be converted to the JT3D-7 configuration during planned engine overhaul. It was determined that P&W engine hardware kits were indeed available for conversion and that such conversion was a common practice in the commercial marketplace. However, neither the engine conversion nor the acquisition of aircraft with the JT3D-7 engines for the JSTARS production program turned out to be an option owing to the high cost of hardware conversion at the time of the planned overhaul. Achieving commonality with other Air Force aircraft, e.g., KC-135E tankers using the same JT3D-3B engine, was judged to be a more economical approach than an upgrade or replacement. In addition, the related Air Force engine overhaul facilities supporting TF33 class engines were looked at.

To understand if there were any engine options available in the marketplace that would improve the aeronautical performance of JSTARS and other of its aircraft, the Air Force commissioned a re-engining roadmap integrated product team (IPT) in 1997. The goal of this endeavor was to analyze the then state-of-the-art engines that were powering the commercial fleets and determine if there was a cost-effective re-engining option that satisfied the Air Force ground rules. Each of the engine manufacturers—P&W, GE/Snecma (CFM International[2]), and Bavarian Motor Works/Rolls-Royce (BMW/RR)—had engines

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[2] CFM International is a joint venture between GE Aviation of the United States and Snecma of France.

that could meet the operational needs of the Air Force. The engines that were studied were the BMW/RR BR-715, which was under development at the time of the 1997 study; the GE/Snecma CFM56-2 and, to a lesser extent, their CFM56-3; and the P&W JT8D-219. Figure 4-1 shows an E-8 JSTARS aircraft with TF33 engines next to an AWACS powered by CFM56-2 engines. As shown in Figure 4-1, modern GE, P&W, and RR engines for large aircraft are larger than the original TF33 engine (and they are heavier as well). The increase in engine weight is offset by the greater reliability, higher thrust, increased fuel efficiencies, and higher operating altitudes. Any of the three engine options could have provided substantial operational benefits to JSTARS while meeting today's noise and environmental requirements and reducing engine maintenance and fuel costs. As noted above, the re-engining option was not incorporated in the JSTARS program at that time due to the high NRE costs of developing the re-engining package and the total acquisition cost of re-engining the fleet.

Subsequent to the IPT's re-engining roadmap study, several more studies were initiated looking at various options such as utilizing higher thrust TF33 engines from the C-141 fleet being retired. The TF33 engine offered a number but not all of the performance improvements sought by the user. The engine is basically of the same vintage as the P&W JT3D-3B and can be made to meet International Civil Aviation Organization (ICAO) Stage III noise standards with the addition of a hush kit, but it cannot be made to meet Stage III emissions standards. Also, being an older technology engine it did not offer the reduced fuel burn, lower cost of ownership, and greater reliability achieved with today's engines. Today, the JSTARS aircraft is still flying with the TF33-3B engines that were installed when the aircraft were first acquired by the Air Force. These older engines are resulting in low mission-capable rates, the highest in-flight engine shutdown rate of all nonfighter aircraft, and a spiraling increase in engine depot costs. Demand by theater commanders for the aircraft continues to grow, raising serious concerns about flight safety and reliability (see Figures 4-2 and 4-3 for E-8 JSTARS data).

The engine shutdown rate for the TF33 is 70 times that of current engines, which indicates to this committee the urgent need to re-engine this aircraft.

FIGURE 4-1 E-8 JSTARS with TF33-102C engines and Royal Air Force AWACS with CFM56-2 engines. SOURCE: Alan van Weele.

FIGURE 4-2 E-8 average flying hours per aircraft each year. SOURCE: Foringer (2006).

Currently all the JSTARS engines are being upgraded from the JT3D-3B configuration to the -7 configuration during their planned overhaul. This upgrade will provide a slight improvement in aeronautical performance but will not significantly reduce the cost of ownership of JSTARS aircraft. It is considered a stopgap measure until a viable re-engining option is introduced. The costs of maintaining the current engine, cowl set, and thrust reversers will still be present for the JT3D-7 engine until a complete new installation has been incorporated into the JSTARS baseline. Depot costs for either the -3B or the -7 engine will continue to increase at a rate that is unsustainable. Since FY03 the depot cost for TF33 engine overhaul has increased by 300 percent, to $1.25 million per engine. With the increasing tempo

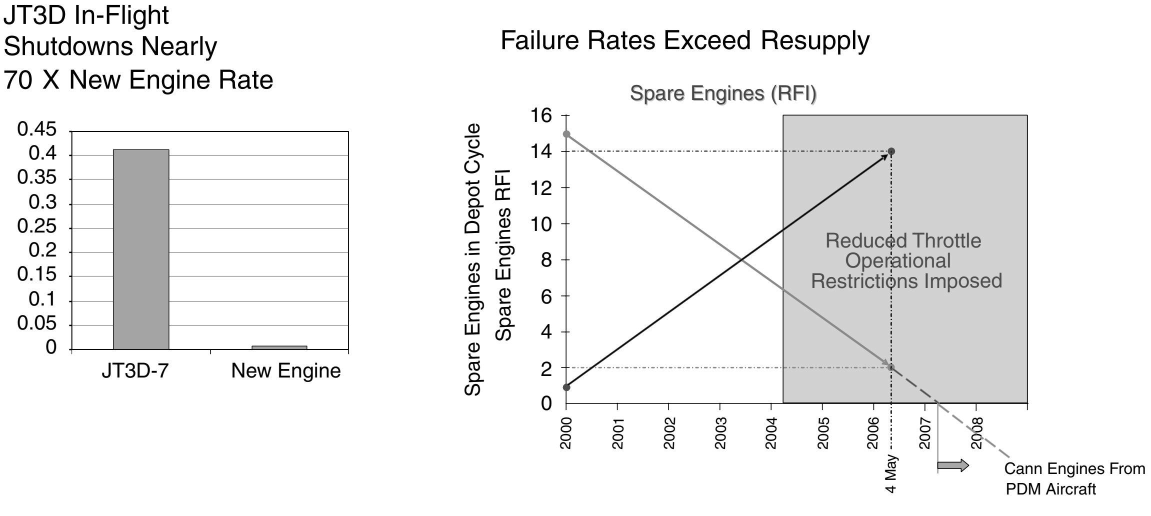

FIGURE 4-3 JT3D in-flight shutdowns. RFI, ready for issue. SOURCE: O'Grady (2006).

of operation and age of the engine, the in-flight shutdown rate and depot cost are expected to increase even faster (Figure 4-4). There are serious issues other than fuel efficiency that need to be considered before deciding on replacement of the TF33 engine on the E-8 through a re-engine program by modern, highly reliable, fuel-efficient engines.

E-3 AWACS PLATFORM

The AWACS aircraft can also be traced to the commercial Boeing 707-320B advanced passenger model that was produced at the end of the Boeing 707 production run. These aircraft had some of the same structural characteristics as the B 707-320C combi/cargo variation that was used as the input aircraft for the JSTARS program. The core input aircraft for AWACS was extensively modified, the distinctive radome was mounted on top of the aft fuselage, and extensive changes were made to the aircraft subsystem to support the mission systems and associated equipment. A new engine was needed to handle the greater drag of the AWACS relative to that of the commercially powered P&W variants. The existing engines had a maximum thrust rating of 19,000 lb, while the new P&W engines were to be an FAA-certified model having 21,000 lb thrust. Concurrently with the AWACS program, Boeing was planning for a new B 707 model known as the B 707-700, which was to be powered with CFM56–2 engines. One aircraft, the last commercially built B 707, was modified for a flight test program by installing 24,000-lb-thrust CFM engines and operated for 2 years gathering performance test data for the planned new model. At the completion of the test program, the aircraft was returned to its original power plant configuration with P&W JT3D-7 engines, modified to an aerial tanker configuration, and sold to the Moroccan Air Force. The B 707-700 program was never launched, but the data provided the foundation for the KC-135R re-engining program and the re-engined AWACS aircraft for the Saudi, French, and British governments.

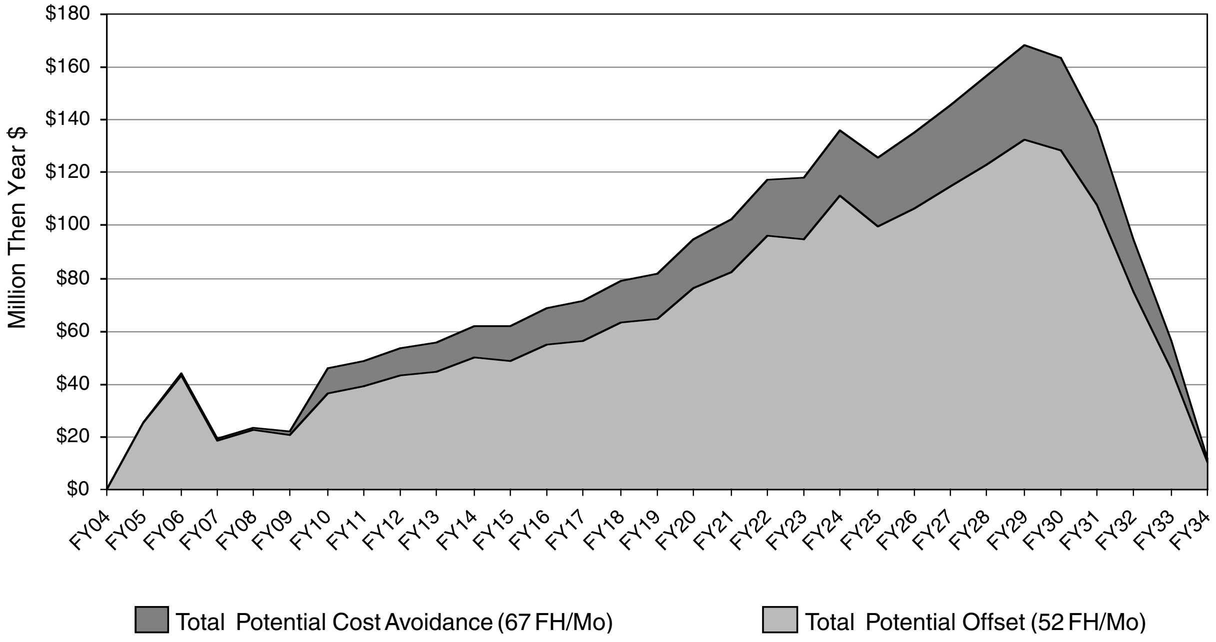

FIGURE 4-4 Cost avoidance potential for the TF33. SOURCE: O'Grady (2006).

The E-3 AWACS family of aircraft has been built with two basic engine configurations. The U.S. (Figure 4-5) and North Atlantic Treaty Organization (NATO) aircraft (Figure 4-6) are powered by the P&W TF33-100 engines, while the British, French, and Saudi governments have aircraft (Figure 4-7) powered by CFM56-2 engines. All of these configurations were part of the aircraft as it went through the production line. Putting new engines on the U.S. and NATO aircraft would now encompass an aircraft modification program with some NRE required. However, a lot of NRE that normally would have been necessary for a re-engine program will not be required since multiple aircraft/engine candidates are available. Each aircraft re-engine program and mission has unique requirements that drive NRE whether or not a specific engine has been integrated onto the platform, and the AWACS aircraft is no different. Although there will be NRE for an Air Force re-engining program, it will be substantially less complicated than it would have been if there were not B 707-320 aircraft flying with engines more modern than the TF33-class engine. When considering a re-engining program for the U.S. AWACS, a number of choices present themselves. The most likely candidate list for a re-engining program includes the GE CFM56-2/-3/-5/-7, P&W JT8D-219, and RR BR-715 engines, as well as several others. All of these candidate engines will require NRE to handle the dual generator requirement of the AWACS aircraft. The dual generator requirement is a good example of the uniqueness of any re-engining program. Even though an engine has been integrated into a similar category/class of aircraft, it is the unique military mission and requirements that drive additional NRE. The complexity and benefits of the modification of an aircraft are related more to the unique requirements than to the engine choice. The committee also has seen the natural tendency to group modifications together to take advantage of the downtime that a re-engining program demands. Other modifications that eliminate line replaceable units like analog gauges, older autopilots, and flight director systems or that add capability like digital displays, data links, and improved navigation systems seem to find their way into the re-engining program. As it has done

FIGURE 4-5 U.S. E3-C AWACS powered by P&W TF33-100 engines. SOURCE: Air Force.

FIGURE 4-6 NATO E3-A AWACS powered by P&W TF33-100 engines. SOURCE: NATO.

FIGURE 4-7 United Kingdom E3-D powered by GE/CFMI CFM56-2 engines. SOURCE: Alan van Weele.

with other platforms having the TF33 engine, the Air Force has studied the potential for re-engining the AWACS aircraft. All of the studies concluded that although there are multiple candidate engines and NRE for this specific platform would be less complicated than most NRE for other platforms, the business cases based on reduced engine maintenance and fuel costs do not justify a re-engining program given the utilization rate and service life. However, this committee believes the Air Force should take another look at a re-engine program for the AWACS aircraft based on eliminating the TF33 engine entirely. An example of successful re-engining is that of the KC-135R aircraft, which gave it the operational capability and fuel efficiency needed to support our nation's growing security needs.

The U.S. AWACS aircraft are excellent candidates for re-engining since the NRE and risk are minimal and significant improvements in fuel efficiency, operational capability, and engine reliability, together with reduced total weapon system support costs, could be achieved.

B-52 AIRCRAFT

While the design of the B-52 bomber dates back to the early 1950s, only B-52H models with TF33 turbofans are still in inventory (earlier models were equipped with older J57 turbojet engines). The 76 aircraft currently in inventory are supported by over 600 TF33-PW-103 engines. The B-52H is currently expected to stay in inventory until 2045.

There have been at least seven studies of re-engining the B-52 since 1997. These studies differed in their assumptions but considered several different choices of engines as well as both direct purchase and various leasing arrangements. Financing is discussed elsewhere in this report. The studies reached similar conclusions: Newer commercially available engines offer significant fuel savings; a re-engining program would be very expensive, more than can be justified by fuel savings alone; and significant improvements in operational employment and performance can be expected. However, all these previous life-cycle studies significantly underestimated the increase in costs for both TF33 repair at the depot and fuel. The cost per engine overhaul grew from $286,000 in FY99 to $1.025 million in FY06. The B-52 is unique in that is uses eight engines, which were the largest jet engines available at the time. Since then, engine thrust capability has grown severalfold, so that it is possible to replace each pair of engines with a single larger turbofan with the same or greater thrust. There are many technically viable candidate engines available for re-engining, all offering fuel savings of 25 percent or more. These range from variants of engines now out of production (such as the JT8D and CFM56-2, for which production would be restarted), to engines currently in production for commercial or military uses (the PW F117—PW2040 is the commercial version—the RR RB211-535, and the GE CF34-10), to engines that exist only in concept (a PW F119 core powering a higher bypass fan). These engines differ in many respects, including physical size and weight, thrust at takeoff and at cruise, net installed drag, nacelle modifications needed, as well installation and interface details. Most of these engines require the purchase of all new nacelles as well as engines.

Replacing each two-engine pair with one larger engine requires the purchase of all new nacelles and pylons (which can be as expensive as the engines) as well as resolving engine-out recovery issues (since an engine failure of a four-engine aircraft results in a 25 percent loss of thrust rather than a 12.5 percent loss for an eight-engine aircraft). Additional engineering concerns (see Figure 4-8) include cockpit and control interfaces as well as the quickstart capability needed if the B-52 is to continue with its nuclear single integrated operational plan. Also, because unlike the other TF33-powered Air Force platforms, the B-52 carries and releases weapons, safe weapons separation must be ensured, especially for wing-pylon-carried munitions.

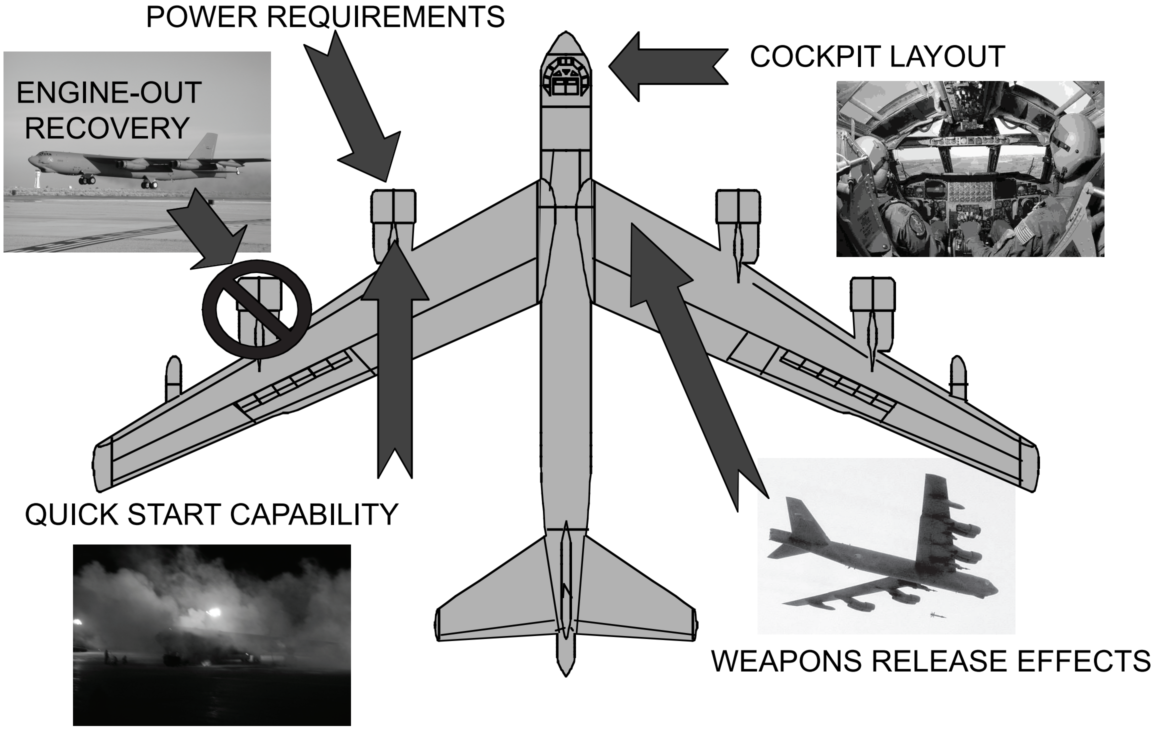

FIGURE 4-8 Technical considerations in B-52 re-engining. SOURCE: Garcia (2006).

The GE CF34-10 is a new commercial engine suitable for B-52 re-engining that was not considered in the re-engining studies referred to above. It is close to the same diameter as the TF33, so that an eight-engine CF34-10 installation would be very similar to that on the current aircraft, possibly obviating many of the engine-out and stores-release concerns engendered when replacing eight engines with four larger ones. The committee did not review either an engineering analysis or a business case for this option.

Like the other TF33-powered Air Force platforms, re-engining the B-52 would reduce both fuel and maintenance costs as well as provide operational benefits such as access to shorter runways, higher takeoff weights at high ambient temperatures, and longer range and endurance.

Reduced dependence on foreign oil, improved operational capabilities, and enhanced Global Power projection are important considerations that should be taken into account in the decision to proceed or not proceed with a re-engining program for the B-52. This committee believes these less tangible benefits, considered in conjunction with the improvements in fuel burn and maintenance costs, swing the argument for proceeding with a re-engining program.

Previous studies showed that fuel savings of 15-20 percent could be realized for the B-52 alone, increasing to 38 percent for a mission when tanker fuel is also a factor. Also, unrefueled mission radius can be increased by 45 percent. Maintenance costs for the B-52 engines have grown much, much faster than anticipated, by severalfold since the last study (DSB, 2004). Also, there are now more engine options available, perhaps reducing the NRE and certification costs, and fuel is much more expensive, making the case for re-engining even stronger.

KC-135 AIRCRAFT

The Boeing KC-135 Stratotanker has been the mainstay of the Air Force aerial refueling fleet for the past 50 years. During that time, the aircraft have provided cargo capability and in-flight refueling for transport, bomber, reconnaissance, and fighter aircraft of the Air Force, the Navy, the Marine Corps, and the militaries of allied nations.

The original Boeing KC-135A Stratotanker utilized Pratt & Whitney J57-P-59W engines augmented with water injection at takeoff. In service, the capabilities of these engines imposed limitations on the takeoff maximum gross weight of the aircraft, especially on hot days. In the mid-1970s, Boeing produced a prototype 707 aircraft with high-bypass CFM56 engines, the 707-700. This configuration was intended to provide commercial customers with higher thrust, improved fuel economy, lower operating and maintenance costs, and much quieter operation. Full-scale production of this model was not pursued by Boeing, however, and the program was canceled. The Air Force expressed an interest in the CFM56 engine for its KC-135 fleet, and after reviewing the design and performance, elected to award Boeing a contract in 1979 to engine the KC-135A with the CFM56-class engine (military designation F108-CF-100 and commercial designation CFM56-2B-1). KC-135 aircraft configured with new CFM56-2B-1 engines were redesignated KC-135R.

Figure 4-9 depicts the various modifications made to the KC-135A that accommodated the CFM56 engine and allowed increasing the maximum gross weight of the aircraft from 301,000 lb to 322,500 lb. Although no modification was required for putting on the new CFM56 engines, the landing gear and nose wheel steering were modified, allowing an increased gross weight, which in turn allowed the Air Force to utilize the full capacity of the integral fuel tanks.

These airplanes have been re-engineered with the CFM56-2 engine models that provide better takeoff performance, range, and fuel burn than the J57-powered KC-135A. The A to R benefits are as follows:

- More fuel efficient
  - —CFM56 is 31 percent more fuel efficient than the J57.
- Cheaper to maintain
  - —Significantly reduced unscheduled maintenance,
  - —Fewer depot maintenance hours, and
  - —F108 (military designation for the CFM56-2) features in common with the CFM56-2 allow it to take advantage of the large commercial usage.
- Better aircraft performance
  - —Reduced aircraft takeoff roll: 38 percent,
  - —Increased thrust: 41 percent,
  - —Increased fuel offload: 15 percent,
  - —Noise reduction: 95 percent, and
  - —Reduced emissions: 97th percentile.

A KC-135 aircraft equipped with CFM56-2B-1 engines shows significant improvements:

- 60 percent increase in thrust from the KC-135A baseline,

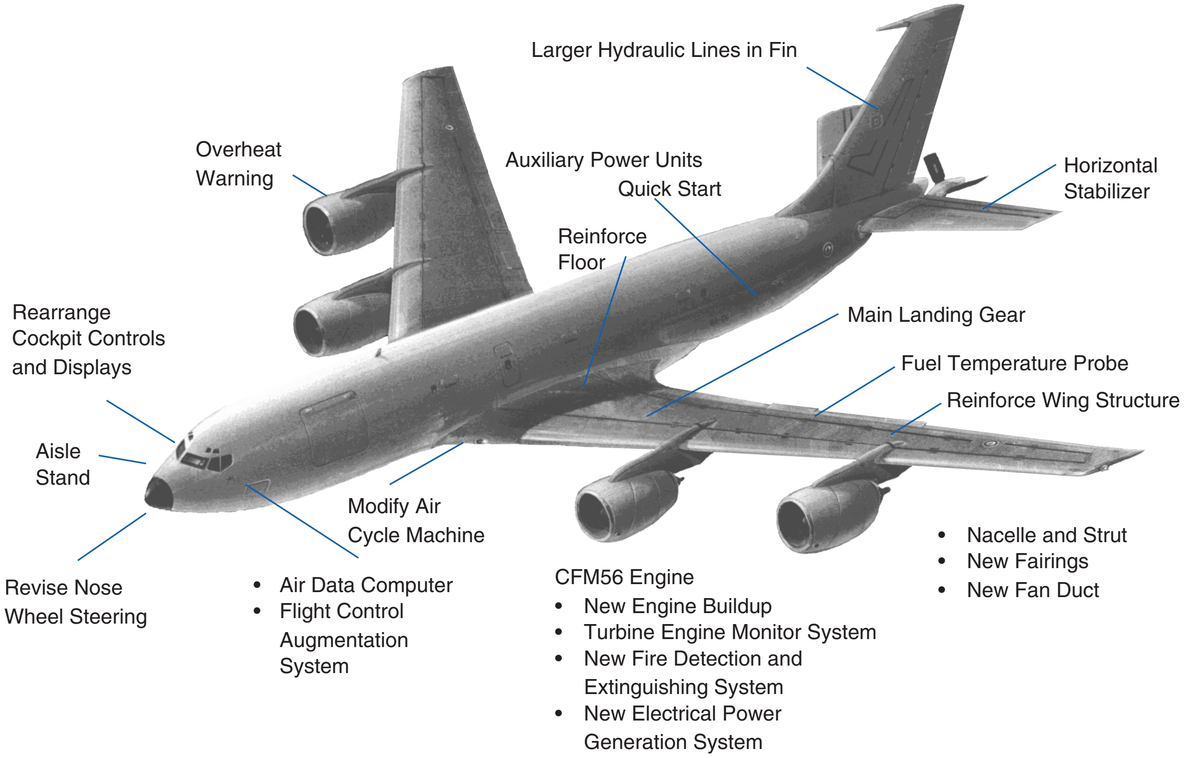

FIGURE 4-9 The KC-135 A to R. SOURCE: Shuppert (2006).

- 27 percent improvement in fuel efficiency,
- 98 percent reduction in noise area impacted during takeoffs, and
- 20 percent reduction in critical field length at increased takeoff weight.

The last KC-135A tanker modification with CFM56-2B-1 engines was completed in 1995.

In 1981 the Air National Guard and the Air Force Reserve began their own program to re-engine 161 KC-135A aircraft with TF33-PW-102 engines and struts procured from retiring commercial 707 aircraft. These aircraft received the designation KC-135E. Although not as significant as the improvements of the KC-135R, the KC-135E did provide some advantages over the KC-135A:

- 30 percent increase in thrust,
- 14 percent decrease in fuel consumption, and
- 85 percent reduction in noise area impacted during takeoffs.

After completion of the program to re-engine its KC-135A aircraft, the Air Force started a program to re-engine its KC-135E tankers with the CFM56-2B-1. For budgetary and other reasons, however, 114 of the tankers have not been so modified. From 1981 to 2006, Boeing modified a total of 470 KC and RC-135 aircraft with CFM56 engines.

After the delivery of the last RC-135 to receive CFM56-2B-1 engines in May 2006, the re-engine production line was shut down. The Air Force has contracted with Boeing to maintain the capability to restart the CFM56-2B-1 re-engine line if DoD and the Air Force elect to re-engine part or all of the remaining KC-135E aircraft. Several rough order-of-magnitude estimates of the costs of restarting the re-engining line have been completed by Boeing and GE. The latest, sent to this committee in June 2006, estimated start-up costs of approximately $25 million and recurring costs of $33 million per aircraft.

The KC-135R does offer significant improvements in reliability, maintenance, and operational performance over the KC-135E with TF33-PW102 engines:

- 18 percent reduction in specific fuel consumption,
- 20 percent improvement in critical field length,
- 25 percent improvement in time to climb, and
- 20 percent improvement in fuel offload.

A number of upgrades had been and are still being introduced in commercial CFM56 engines. Examples are 3D and tech insertion programs. They result in fuel savings and increased reliability, and the Air Force should consider them for upgrading the F108 fleet.

TF33-PW102 depot maintenance costs have been increasing rapidly, with the depot cost per engine in FY06 equaling $1.25 million. The Air National Guard expects that depot cost will continue to increase less than 3 percent each year. Since FY03, the depot maintenance cost for the TF33-PW102 engine has increased 300 percent.

The Air Force has stated its intention to retire the remaining 114 aircraft equipped with TF33 engines by the end of FY08. If indeed it decides to do this it makes no economic sense to restart the re-engining program.

As noted above, the Air Force may realize significant savings and efficiencies by thinking of its engine assets in terms of engine model type rather than individual weapon system or platform. The case for improving operational efficiencies and investment strategies might be strengthened by extending it to include the common engines used by the other services. This view of volume effects on strategic acquisition and operations could prevail insofar as the Air Force has been designated the lead service on aircraft engines. This should provide the mechanism for a DoD-wide approach to fuel savings, extending from the focused intraservice R&D to produce new fuel-efficient propulsion systems to re-engining or upgrades of the fleets. One nonfighter engine used by more than one service is the T56, which is used by both the Air Force and the Navy in the C-130 fleets. The T406 engine is used in the V-22 in multiple services.

Finding 4-1. The TF33 engine population is one of the largest and one of the oldest in the Air Force inventory and powers aircraft having some of the most critical missions.

Finding 4-2. The maintenance costs on all segments of the TF33 population have escalated considerably over the past 7 years, outpacing the inflation rate and the budgeted allocations.

Finding 4-3. The in-flight shutdown rate for the engine is one of the highest in the Air Force fleet, and readiness is negatively impacted by high removal rates.

Finding 4-4. TF33 engines, which were once ubiquitous in the civil fleet, are no longer in service in developed nations because they flout environmental restrictions.

Finding 4-5. The TF33 engine is deployed in several different model configurations on the various platforms and displays a range of thrust and installation features.

Finding 4-6. The weapon systems themselves have varying demands in terms of compressor bleed requirements, power extraction, external weapon location and release interference, and radar field of view.

Finding 4-7. All of the TF33-powered aircraft have been the subject of extensive re-engining studies, and in several cases either flight demonstration programs or successful operational models have been completed. This includes the E-8 re-engining activity currently in progress.

Finding 4-8. Several candidate engines have attributes that could contribute to significant fuel savings and reduced maintenance costs.

Finding 4-9. The fuel saving from re-engining with modern engines will not, in and of itself, justify the cost of the program owing to the relatively low utilization rate, the high cost of fuel, the small fleets, and the short planned service life.

Conclusion 4-1. The removal of the TF33 engine from the inventory and its replacement with modern, long-overhaul-interval engines will significantly improve operating cost and readiness and save fuel.

Conclusion 4-2. The differing requirements of the various weapon platforms may mean that each platform needs a different engine.

Conclusion 4-3. The operational experience with re-engined versions of some of the systems makes such re-engining very low risk and highly predictable in terms of nonrecurring and operational costs.

Recommendation 4-1. The Air Force should approach re-engining of the aircraft powered by the various models of the TF33 engine on a holistic basis with the goal of removing the engine(s) from the inventory.

Recommendation 4-2. The Air Force should immediately conduct for each TF33-engined weapon system an internal review and competitive re-engining study that looks at fuel savings, operational capabilities, and maintenance costs as figures of merit in order to select the best option.

Recommendation 4-3. The Air Force should give strong consideration to employing commercial support practices and contractual arrangements to minimize infrastructure and staffing costs.

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5

Recurring and Nonrecurring Cost Estimations

This chapter details the approach used to estimate the recurring and nonrecurring costs of the re-engining and engine modifications proposed in Chapter 1. The committee employs various methods to estimate the costs and benefits of switching to newer engines with better fuel efficiency and improved reliability. For each of the alternatives, it calculates the net present value (NPV), which lets it see if the Air Force might be able to recoup its investment costs through savings from lower fuel consumption and fewer hours spent in maintenance.

ANALYSIS APPROACH

The life-cycle cost (LCC) section includes an analysis of LCC and a partial NPV analysis for all re-engining and engine modification alternatives. This analysis is not a complete benefit/cost analysis since not all benefits associated with engine modifications, re-engining, and airframe modification to achieve fuel savings or reliability, maintainability, and availability improvements, and/or performance improvements are monetized. It does not attempt to account for the residual value of engines (which, in general, could improve the case for re-engining or engine modification) after re-engined airframe retirement or for any national benefit from reduced dependence on imported foreign oil.

The committee believes that no such analysis was feasible within the time constraints of this study. However, it recommends that such an analysis be undertaken on selected options by the Air Force prior to any final decision. In particular, the Air Force should consider the potential cost-saving or capability-enhancing changes to force structure that would be enabled by re-engining existing platforms.

The NPV analysis does, however, look at the recurring and nonrecurring costs as well as the benefits that result from engines having improved reliability and specific fuel consumption (SFC). The analysis is performed for the aircraft/engine combinations listed in Table 5-1.

TABLE 5-1 Aircraft/Engine Combinations

Aircraft Designation	Current Engine[a]	Re-engine Candidate	Re-engining	Engine Modification/ Upgrade
KC-135R	F108 (CFM 56-2)		No	Yes
B-52	TF33 (JT3D)	F117 (4), CFM56 (4), CFM34 (8)	Yes	No
C-5	TF39	CF6-80	Ongoing	No
C-130H	T56 (T56)	AE 2100, PW150	Yes	Yes
KC-135D/E	TF33 (JT3D)	CFM56-2, JT8D-219	Yes	No
KC-10	CF6-50 (CF6-50)		No	Yes[b]
B-1	F101	F101 SLEP, F119, Derivative F119	Yes[b]	Yes[b]
E-3	TF33 (JT3D)	CFM56-2 and -7, JT8D-219	Yes	No
E-8	TF33 (JT3D)	JT8D-219, CFM56-2 and -7	Ongoing	No

[a] Military designations shown. Designations in parentheses are commercial engine equivalents where they exist.

[b] Entries corrected after release of the January 31, 2007, prepublication version of the report. An entry for the C-17 was also deleted at that time.

Nonrecurring Costs

Nonrecurring costs include any costs of the research and development (R&D), testing and evaluation efforts associated with airframe modification, engine modification, nacelle redesign, pylon redesign, other subsystems redesign, flight testing, weapons separation design efforts related to new tooling requirements, and all systems engineering and program management by contractors and the government.

Recurring Costs

The recurring costs would include the unit cost of new engines, of installation kits (engine and airframe modifications), of logistical support, of training, tooling, and test equipment, of spares, data, etc.

Costs and Benefits to Operations and Support

The benefits to operations and support (O&S) would include the impact of fuel savings attributed to more fuel-efficient engines. They also include the impact of improvements in engine reliability and maintainability on cost of mission maintenance personnel, consumables, depot-level reparables (DLRs), and engine overhaul. These elements are defined by the Cost Analysis Improvement Group (CAIG) in the Office of the Secretary of Defense (OSD) as follows:

- Maintenance personnel cost reflects the pay and allowances of military and civilian personnel who support and perform maintenance on the engine. Depending on the maintenance concept and the organizational structure, this element will include maintenance personnel at the organizational level and, possibly, the intermediate level.
- Consumables are materials and bits-and-pieces repair parts that are used up or consumed during maintenance.
- DLRs are the unit-level cost of reimbursing the stock fund for purchases of the DLR spares (also referred to as exchangeables) used to replace initial stocks. DLRs may include repairable

individual parts, assemblies, or subassemblies that are required on a recurring basis for the repair of major end items of equipment.

- And, finally, depot overhaul costs are typically for the most complex work that requires expertise or equipment not available at the organizational or intermediate levels.

Maintenance and Fuel Savings

As shown in Figure 1-1 in Chapter 1, the Air Force uses over half of the fuel consumed by DoD, and a significant share of that fuel is used to power nonfighter aircraft. Further, as reported in the Air Force Total Ownership Cost (AFTOC) database and as displayed in Figure 2-1 in Chapter 2, the cost of engine O&S was about 20 percent of all aircraft O&S costs in FY05. Engine maintenance and fuel costs form a substantial portion of the Air Force's budget.

Re-engining nonfighter aircraft presents the Air Force with an opportunity to consider more fuel-efficient and reliable engines. Similarly, modification or upgrade of current engines can incorporate design improvements to improve reliability and fuel efficiency. However, the costs of these improvements are not inconsequential. Thus, the benefits of the fuel savings and reduction in maintenance need to be balanced against the cost of the investments.

The next section describes the methodology used in the NPV analysis of the nonrecurring and recurring costs, and fuel and maintenance savings.

METHODOLOGY AND BASIS FOR THE ESTIMATE

There are three standard methods of estimating costs: analogy, parametric, and engineering bottom-up. The analogy method is fairly simple. It draws from actual program costs or historical cost information from a legacy program of similar technology and complexity. Sometimes simple adjustments to the legacy data may be necessary to facilitate estimating the cost of the new system. The second way to estimate cost is parametric modeling, a statistical method that also uses historical data, regressing cost or hours—the dependent variable—against a series of independent variables. These independent variables are often parameters related to the system performance: physical or programmatic characteristics. The resultant relationship is often called a cost-estimating relationship (CER). The third method is the engineering bottom-up method, which is a much more detailed approach. Where the committee was unable to obtain the necessary information needed to use one of the above methodologies, it relied on expert judgment.

The committee's analysis includes estimates of nonrecurring and recurring costs based on CERs developed by RAND for use in the conceptual design of new aeronautical systems and previously published (Younossi et al., 2002). Table 5-2 summarizes these CERs.[1] The RAND CER for the nonrecurring costs estimates the cost of developing a new derivative engine. For the purposes of this analysis, the committee assumes that the re-engining effort amounts to only 10 percent of the costs estimated by

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[1] For the prepublication version of this report, the committee estimated the recurring costs for the various aircraft/engine combinations using the RAND CER for recurring unit costs (Table 5-2) or, for those cases for which it was available; the committee used market data to estimate recurring costs. This method meant, however, that some of the aircraft/engine cost estimates based on CERs were being compared with other estimates using both CERs and market data. When the committee's analysis was redone for this final report, recurring costs were estimated using the RAND CER only. The reason for this change was to provide a consistent source of data.

TABLE 5-2 Nonrecurring and Recurring Cost Estimating Relationships

Cost Element	Methodology
Nonrecurring costs for derivative engine	lnrd01m = −39.422 + 5.066 lnritf − 1.299 lnTSFC + 0.582 lnfsth (4.45) (−3.89) (5.32) R-squared = 0.8332 Adj R-squared = 0.8068 Root MSE = 0.40575 lnrd01m, natural log of the development cost in million 2001 dollars; lnritf, natural log of the rotor inlet temperature (F°); lnTSFC, natural log of the thrust-specific fuel consumption (lb/hr/lb); and lnfsth, natural log of full-scale test hours.
Recurring unit costs	lnT1 = −10.4 − 8.55 lnslope + 0.482 ab + 1.162 lnritf + 0.2615 lndrywt (−13.02) (4.595) (3.626) (2.416) R-squared = 0.9703 Adj R-squared = 0.9641 Root MSE = 0.13703 lnT1, natural log of the production price for first unit in million 2001 dollars; lnslope, natural log of the cost improvement curve slope; ab, binary variable (1) if afterburning engine, (0) if not; lndrywt, natural log of the dry weight for the engine (lb); and lnritf, natural log of the rotor inlet temperature (F°).

the RAND CER since the candidate engines are already developed. This amount estimated is thereby intended to account for the integration and additional testing efforts only.[2]

Fuel Consumption

The usual practice in figuring fuel consumption, particularly in the case of acquiring a new system, is to specify a spectrum of mission profiles and meticulously calculate the fuel burn rate averaged over that spectrum. For new system acquisition, there is little alternative to this procedure since there is no experience base for an aircraft that does not yet exist. For all aircraft under consideration in this study, the committee has a very substantial experience base from which to derive fuel burn rates (pounds or gallons per hour). These fuel burn rates are the average over a mix of mission profiles actually experienced. The committee followed the general principle that these average fuel burn rates represent the best information available absent compelling evidence to the contrary. Assuming that the mix of mission profiles in future will remain the same as the mix already experienced, a very good estimator of fuel

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[2] This approach may not capture all nonrecurring costs; for example, replacing eight engines with four may require additional modifications to the aircraft such as a larger tail to deal with an engine-out flight condition. In general, however, nonrecurring costs were not primary drivers of the results, so the committee deemed the 10 percent CER approach to be reasonable for the purposes of its analysis.

TABLE 5-3 Formulas for Estimating Fuel Consumption and Repair Costs for a Single Aircraft

Cost Element	Parametric Estimating Relationship
Fuel consumption (gal/aircraft-yr)	Fuel consumption = Fuel consumption$_{\textbf{Current}}$ * TSFC$_{\textbf{New}}$/TSFC$_{\textbf{Current}}$
Repair cost ($/aircraft-yr)	Repair cost = 1188070710 * flying hours ^0.7013 * max power ^0.7975 * removal rate ^0.4421 * e^(MQT date * −0.0103)

consumption rates for re-engined/modified-engine aircraft is obtained from the ratio of current to the re-engined installed thrust-specific fuel consumption (TSFC) taken at cruise condition.[3]

Engine Repair Cost

The RAND CER for engine repair is based on cost and usage data from the AFTOC database from FY98 to FY04. The relationship predicts engine-related O&S costs per aircraft MDS fleet per year in the four O&S cost elements described in the preceding section. These costs are measured in FY04 dollars. Inputs, or independent variables, in the relationship are maximum thrust per aircraft, the year of military qualification test (MQT) for the engine, the mean time between removals (or engine time on wing[4]), and whether the aircraft and engine are flown by Air Force Reserve components or the active Air Force. Thrust and MQT year data were obtained from *The Engine Handbook* (U.S. Air Force, 2005). Removal information was obtained from the Air Force's Comprehensive Engine Management System (CEMS) database. The estimates used in the analysis were based on this relationship with the exception of the C-130 and KC-10 estimates which were drawn from contractor briefings. Table 5-3 shows the estimating relationships.[5]

ASSUMPTIONS, INPUTS, AND DATA

This section presents the assumptions used in the analysis, the technical and fleet information needed in the estimating relationships, and the sources of those data. The ground rules and assumptions used in the NPV analysis are these: (1) all costs are in or are adjusted to millions of FY06 dollars using a 3 percent deflator; (2) a nominal discount rate of 5.2 percent is used based on Office of Management and Budget recommendations; (3) a fuel cost of $2.50 per gallon was assumed, and the committee performed sensitivities using 3, 6, and 9 percent fuel cost escalation rates to demonstrate the influence of potentially rising fuel costs.[6] Maintenance costs were assumed to grow at 3 percent per year.

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[3] To complete its analysis, the committee used the simplifying assumption equating fuel burn improvement to TSFC improvement. The committee understands there is more to fuel burn than cruise TSFC. Installation and matching have important influences as well, and these effects can differ from engine to engine on the same airplane. Flight test data can yield qualitatively and quantitatively different results for fuel burn than CER analysis yields. Thus engines should not be compared on this basis alone.

[4] The number of flying hours per engine before it is removed for repair; it is a standard measure of engine reliability.

[5] In some re-engining cases considered here, the planned life of the aircraft in flight hours is less than the overhaul interval for candidate modern commercial engines. Thus the aircraft could be expected to be retired before its engines needed a major overhaul. Since such overhauls represent a significant portion of the maintenance cost, the actual maintenance cost of those engines may be less than that estimated by the approach.

[6] From 2003 to 2006, the actual inflation factor was 25 percent, and that may be driving the upgrade interest at this time. The large increase in fuel prices in recent years can be placed in a longer historical context of far smaller increases. The committee selected 3, 6, and 9 percent as annual fuel inflation rates, consistent with a wide spectrum of long-term projections.

TABLE 5-4 Assumptions for Fuel Savings

Candidate Aircraft/Engine Configuration	SFC/Fuel Burn Improvement (%)[a,b]
Re-engining	
B-1/F119/5.0	10.0
E-3/CFM56-2B-1	11.8
E-3/JT8D-219	6.2
E-3/CFM56-7B22	19.1
E-8/CFM56-2B-1[c]	–
E-8/JT8D-219[c]	–
E-8/CFM56-7B22[c]	–
KC-135D/E/CFM56-2B-1	15.8
KC-135D/E/JT8D-219	10.4
KC-135D/E/CFM56-7B22	22.7
B-52/F117-PW-100 [4]	24.7
B-52/CF34-10A [8]	15.9
B-52/CFM56-5C2 [4]	26.6
C-5/CF6-80C2 (F103-GE-102)[d]	–
Engine modification	
KC-135 R/T/CFM56-A2	2.1
B-1/F101 Mod	10.0
KC-10/CF6-50 Mod	0.3

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.
[b] Values listed are based on estimates obtained from contractors.
[c] E-8 re-engining already ongoing.
[d] C-5 re-engining already ongoing.
SOURCE: Committee generated.

Improvements in fuel efficiency are accounted for by the change in TSFC, installed where available (see Table 5-4). In the table, the fuel burn improvement is calculated as the TSFC of the current engine configuration less the TSFC of the candidate. A positive improvement figure indicates that the re-engined or modified aircraft/engine configuration candidate is more fuel efficient than the current configuration. A negative improvement figure indicates that the re-engined or modified candidate engine is less fuel efficient.[7]

Table 5-5 lists the data used as inputs to the estimating relationships for recurring and nonrecurring costs, fuel costs, and repair costs. Table 5-6 shows where the committee obtained the information it used for the NPV analysis.[8] While the committee tried hard to draw information from public sources such as

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[7] For the prepublication version of this report, the committee took the TSFC values of the current aircraft/engine and candidate configurations from a variety of sources, including *The Engine Handbook* (U.S. Air Force, 2005), contractor estimates, and *Jane's Online*. In some instances, the TSFC performance of a current engine at one set of operating conditions was being compared to the TSFC performance of a candidate replacement engine at a different set of operating conditions; that is, apples-to-oranges comparisons. When it redid its analysis for this final report, the committee requested TSFC values directly from the engine contractors and, so it could make apples-to-apples comparisons, the committee requested the TSFC values for the current engines and the candidate replacement or modified engines be for the same typical cruise conditions.

[8] Two of variables needed for the fuel consumption and engine maintenance regressions but missing from the table are the slope of the unit learning curve and full-scale-test hours; they were assumed to be at their recent historical average—0.97 and 9,189 hr, respectively.

TABLE 5-5 Inputs to CERs

Re-engining: Current Configurations and Candidates	Number of Engines	SFC at Maximum Power lb/lb-hr	Ratio Maximum TOW to WE	After-burning? (1 = yes; 0 = no)	Maximum Power per Engine (lb thrust)	Mean Shop Visit Rate (Removals/ 1,000 Hours)	Engine Military Qualification Date	Engine Dry Weight (lb)	Rotor Inlet Temperature (F°)
B-1/F101-GE-102[a]	4	2.460	2.62	1	30,000	4.410	1983	4,428	2550
B-1/F119/5.0	4	2.214	2.62	1	37,000	4.410[d]	2001	4,150	3092
E-3/TF33-PW-100A[a]	4	0.560	2.04	0	21,000	0.610	1974	4,790	1750
E-3/CFM56-2B-1	4	0.363	2.04	0	21.634	0.093	1982	4,610	2228
E-3/JT8D-219	4	0.454	2.04	0	21,000	0.151[d]	1985	4,612	2420
E-3/CFM56-7	4	0.360[d]	2.04	0	22,700	0.050[d]	1996	5,234	2228
E-8/TF33-PW-102C[a,b]	4	0.535	1.94	0	18,000	0.970	1963	4,260	1600
E-8/CFM56-2B-1[b]	4	–	–	–	–	–	–	–	–
E-8/JT8D-219[b]	4	–	–	–	–	–	–	–	–
E-8/CFM56-7[b]	4	–	–	–	–	–	–	–	–
KC-135D/E/TF33-PW-102[a]	4	0.535	2.65	0	18,000	0.700	1982	4,260	1600
KC-135D/E/CFM56-2B-1	4	0.363	2.65	0	21,634	0.093	1982	4,610	2228
KC-135D/E/JT8D-219	4	0.454	2.65	0	21,000	0.151	1985	4,612	2420
KC-135D/E/CFM56-7	4	0.360[d]	2.65	0	22,700	0.050[d]	1996	5,234	2228
B-52/TF33-P-103[a]	8	0.520	2.87	0	17,000	0.970	1960	3,905	1600
B-52/F117-PW-100	4	0.347	2.87	0	40,440	0.194[d]	1987	7,122	2400
B-52/CF34-10A	8	0.370	2.87	0	18,500	0.080	2006	3,700	2200
B-52/CFM56-5C2	4	0.320	2.87	0	31,000	0.100	1991	5,670	2400
C-5/TF39-GE-1C[a]	4	0.315	2.14	0	40,805	0.700	1969	7,186	2350
C-5/CF6-80C2[c]	4								
KC-135 R/T/CFM56-2B-1[a]	4	0.3630	2.65	0	21,634	0.092	1982	4,610	2228
KC-135 R/T/CFM56-2B-1 (Mod)	4	0.3557	2.65	0	21,634	0.069	1982		
B-1/F101 F-101-GE-102[a]	4	0.5750	2.62	1	30,000	2.760	1985	4,448	2550
B-1/F101 Mod	4	0.5175	2.62	1	30,000	1.290	2012		
KC-10/CF6-50[a]	3	0.3990	2.45	0	51,711	0.750	1972	8,731	2490
KC-10/CF6-50 Mod	3	0.3977	2.45	0					

NOTE: The C-130 information as well as the information in the shaded cells was not needed for the CERs since the fuel and maintenance savings as well as the nonrecurring and the recurring costs were already provided in the discussion in this report. TOW, takeoff weight; WE, weight empty.

[a] Current engine configuration.

[b] E-8 re-engining already ongoing.

[c] C-5 re-engining already ongoing.

[d] Values corrected after release of the January 31, 2007, prepublication version of the report.

TABLE 5-6 Sources of Data

	Maintenance Cost CERs			Production and Development Cost CERs	
Re-engining Candidate	Total Thrust	Mean Shop Visit Rate	Qualification Date	Dry Engine Weight	RIT (F°)
B-1/F119/5.0	Contractor estimate	Assumed no change	Assumption	Contractor estimate	Analogy to similar system
E-3/CFM56-2B-1	*The Engine Handbook*	AFTOC	CFM engine fact sheet	*Aviation Week*	*The Engine Handbook*
E-3/JT8D-219	Contractor estimate	Contractor estimate	*Jane's Online*	*Jane's Online*	Analogy to similar system
E-3/CFM56-7B22	Contractor estimate	Contractor estimate	CFM engine fact sheet	*Aviation Week*	Assumed same as 2B-1
E-8/CFM56-2B-1[a]	—	—	—	—	—
E-8/JT8D-219[a]	—	—	—	—	—
E-8/CFM56-7B22[a]	—	—	—	—	—
KC-135D/E/CFM56-2B-1	*The Engine Handbook*	AFTOC	CFM engine fact sheet	*Aviation Week*	*The Engine Handbook*
KC-135D/E/JT8D-219	Contractor estimate	Contractor estimate	*Jane's Online*	*Jane's Online*	Analogy to similar system
KC-135D/E/CFM56-7B22	Contractor estimate	Contractor estimate	CFM engine fact sheet	*Aviation Week*	Assumed same as 2B-1
B-52/F117-PW100 (4)	*The Engine Handbook*	Contractor estimate	*The Engine Handbook*	*The Engine Handbook*	*The Engine Handbook*
B-52/CF34-10A (8)	*Jane's Online*	AFTOC	GE engine fact sheet	*Aviation Week*	Analogy to similar system
B-52/CFM56-5C2 (4)	*Aviation Week*	Assumption	CFM engine fact sheet	*Aviation Week*	Assumed same as F117
C-5/CF6-80C2 (F103-GE -102)[b]	—	—	—	—	—
KC-135R/T/CFM56-A2	Contractor estimate	Contractor estimate	Contractor estimate		
B-1/F101 Mod	Contractor estimate	Contractor estimate	Contractor estimate		
KC-10/CF6-50 Mod	Contractor estimate				

NOTE: Shaded cells indicate data not used in analysis. RIT, rotor inlet temperature.

[a] E-8 re-engining already in progress.

[b] C-5 re-engining already in progress.

Air Force fact sheets,[9] CFM fact sheets,[10] and GE Engine fact sheets,[11] only a few accurate pieces of information could be so obtained. Information had to be acquired from limited secure-access databases:

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[9] These public documents, available at http://www.af.mil/factsheets/, contain information on many variables about aircraft currently in the Air Force inventory. Total operating weight and weight empty were taken from these sheets.

[10] CFM International is the consortium that produces CFM engines. Public data and history can be found on its Web site: http://www.cfm56.com/engines/.

[11] GE fact sheets are available at http://www.geae.com/engines/.

AFTOC,[12] *Jane's* and *Jane's Online*, *Aviation Week*,[13] contractor presentations to the committee, and finally, proprietary datasets. When no information was available for a given system, as was often the case for rotor inlet temperature, data for an analogous system were substituted.

NET PRESENT VALUE ANALYSIS

The partial NPV model calculates the costs and benefits of modifying or replacing an engine for an entire fleet of aircraft, with the costs being the nonrecurring and recurring costs for development, installation, and testing of the new engine and the benefits being the savings due to lower fuel consumption and less maintenance. These costs and benefits are calculated annually, permitting the construction of a cumulative discounted cash flow profile. Nonrecurring costs are apportioned over the first few years of the re-engining,[14] and recurring costs are allocated to the time when the aircraft is converted. Fuel and maintenance savings are calculated annually and persist until the fleet is retired.[15] The model assumes that the current fleet of aircraft will continue to run at the current rate for annual engine hours until estimated retirement dates.[16]

Figure 5-1 demonstrates the mechanics of the model for a B-1 re-engining with a F101 modification. The three solid lines indicate cumulative discounted cash flows—assuming a different discounting factor for the fuel costs—summing in present value as years progress (from left to right). In the first 7 years, nonrecurring and recurring investments are being made, and the net cash flow is negative. But as aircraft are converted to a new engine, positive savings in fuel costs and maintenance are seen immediately thereafter. The dashed line represents the fleet size. As the figure shows, starting around year 25, the fleet gradually retires from service, and the net benefits no longer accumulate after year 32, by which time the entire fleet has been retired. It should again be noted that the analysis makes no attempt to assess the financial benefits associated with the resale value of low-hour engines following the retirement of re-engined airframes.

Next, the committee collects the summary results of the NPVs for all candidates and displays them in tabular form. The summary tables include two sets of data:

1. The number of years to break even on the investment (for the B-1 engine modification illustrated in Figure 5-1, these are 8.0 years, 7.7 years, and 7.4 years for 3 percent, 6 percent, and 9 percent fuel escalation, respectively, as shown by the points at which the curves cross the horizontal axis.)
2. The cumulative cash flow at the 20-year point, in this case \$470* million, \$610* million, and \$815* million for 3 percent, 6 percent, and 9 percent fuel escalation.[17] (To ensure consistency for purposes of interpretation, the results in Tables 5-7 and 5-8 are based on no retirements before breakeven or the 20-year point, whichever is greater, even if earlier retirement is expected.)

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[12] AFTOC, the Air Force Total Ownership Cost management information system, contains financial and logistic data on the current fleet of Air Force aircraft. A user account is required for access to the system, which is restricted to cleared personnel only. See more at https://aftoc.hill.af.mil/. Data on flying hours and mean time between services were taken from AFTOC.

[13] All references to *Aviation Week* are to the article "Outlook/specifications: Gas turbine engines," in *Aviation Week and Space Technology,* January 17, 2005, pp. 122-134.

[14] The apportionment is 40 percent in the first year, 40 percent in the second year, and 20 percent in the third year. Different spend-out patterns were tried, with insignificant impacts on overall NPV.

[15] Fuel usage and maintenance requirements are determined from two estimating relationships: the first estimates the number of gallons of fuel burned and the second estimates annual maintenance costs.

[16] However, the model does not take into account the reconstitution of the fleet with a set of future aircraft after the current fleet retires.

[17] Asterisks denote values corrected after release of the January 31, 2007, prepublication version of the report.

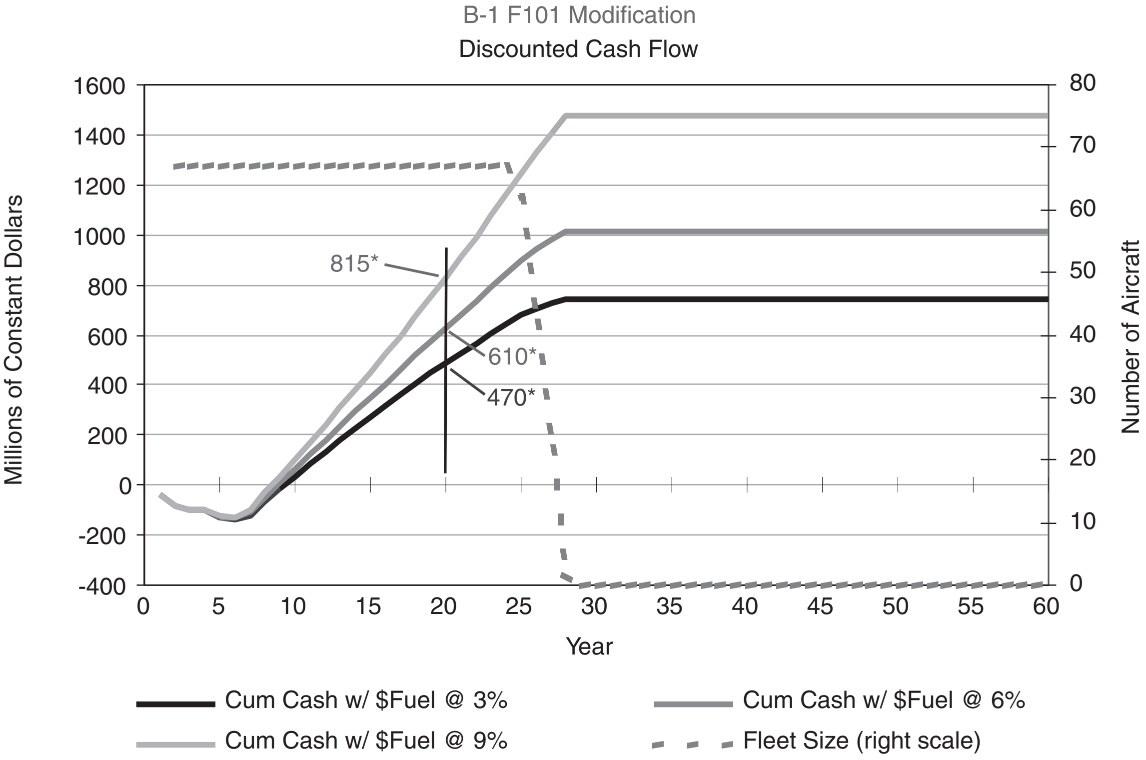

FIGURE 5-1 B-1/F101 modification cash flow analysis. *Values corrected after release of the January 31, 2007, prepublication version of the report.

Table 5-7 displays the result of the NPV calculation for all the re-engining alternatives. It lists the fleet size, the annual flight hours, changes in thrust (if applicable), annual fuel consumption of the original fleet, fuel savings as a percentage and in millions of gallons of fuel saved per year for the re-engined fleet; estimated savings on maintenance cost as a percentage and in millions of dollars per year; the production costs for each engine replaced; and the total development cost. The next three columns list the number of years to recoup the investment if fuel costs increase uniformly at 3 percent, 6 percent, and 9 percent per year. The last three columns show the cash flows estimated at the 20-year point for the same set of fuel cost increases. The cells of the table that recoup investment costs in less than 20 years and therefore have positive cash flow at the 20-year point are all shaded. If the criterion for a good business case is to recoup the investment in 20 years[18] or less and if fuel costs are expected to rise at 3 percent per year and the discount and inflation rates are expected to be as discussed previously, then the C-130H/AE2100, C-130H/PW150, E-3/CFM56-7B22, and B-52/CFM56-5C2[4] options meet the criterion. If, on the other hand, fuel costs are expected to rise faster, then more re-engining candidates will meet the criterion, as indicated by the shaded cells of the table for the higher rates (6 percent and

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[18] The committee's choice of using 20 years as the point to estimate cash flows is arbitrary. For an actual case, the Air Force might use a different criterion.

9 percent) of fuel cost increases. Finally, if the criterion is to recoup investment in some number of years different from 20, the appropriate columns of the table can be used to determine whether the criterion will be met. (All the above assume of course, that the aircraft will not be retired before the criterion is met.) Table 5-8 displays the results for all the potential engine modification alternatives in the same format and is interpreted the same way. It is generally easier to make a business case for engine modifications than for complete re-engining when such modifications improve efficiency or reliability, because the costs are generally comparatively low. At a fuel cost increase of 3 percent per year, the C-130H/T56-A427, B-1/F101, and KC-10/CF6-50 modifications meet the 20-year-payback criterion. With higher rates for fuel cost increases, the C-130H/T56-S3.5 modification comes into play, as can be seen from the shaded cells. The KC-10 savings are due almost exclusively to lower maintenance costs and to the absence of development costs.

In addition, for those who believe that a burdened fuel cost should be used, Table 5-9 shows the results of a sensitivity analysis run assuming various burdened rates of fuel. The figure shown is the number of years until payback for each candidate, under the specified total burdened cost of fuel—$2.50, $5, $10, $20, or $40 (see Appendix G for a sensitivity analysis). The total cost is assumed to have two components: (1) a raw fuel cost that starts at $2.50 a gallon and increases at 6 percent annually and (2) the remainder, an overhead component increasing at 3 percent per year.[19] Care must be taken in interpreting these results since to realize the savings implied by the estimates generally implies a significant change to the infrastructure or to some other element of the burdened cost, and it is often difficult to imagine how this might come about absent significant changes in force structure, basing, and/or operating practices. As can be seen from the shading on the chart, if one believes strongly enough in high burdened fuel costs, a strong business case can be made for almost any proposal.

Finally, it should be remembered that the analysis does not consider the resale value or the recovery value of the engines following retirement of the re-engined airframes.

SUMMARY

The committee considers the analysis results presented in this chapter to be indicative of trends and directions rather than definitive answers and the results cannot and should not be used to differentiate between specific engines on an airframe. Despite the presentation of the committee's analysis results ("years required to recoup investment" and "cash flow at 20-year point") in the tables as precise numbers resulting from the committee's calculations, it is imperative they be viewed and used as approximate estimates, each surrounded by some amount of uncertainty. Before making actual re-engining decisions, the Air Force would have to do much more thorough and detailed analysis than that done by the committee. The Air Force analysis would require higher confidence estimates of input values—for example, for fuel burn improvement and recurring costs—and it would include considerations not dealt with by the committee's analysis—for example, mission impacts.

The committee used its analysis to identify the aircraft for which there was a potential life cycle cost benefit to re-engining or engine modification. That is as far as the results presented in this chapter can be taken.

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[19] That is, if the fully burdened fuel cost is $40 a gallon today, $2.50 of that is raw fuel cost and $37.50 is overhead burden. In the NPV model, 10 years from now, raw fuel costs $2.5 * 1.06^{10}$ = $4.48 a gallon, while overhead is $37.5 * 1.03^{10}$ = $50.40 a gallon, for a total of $54.88 a gallon.

TABLE 5-7 NPV Analysis Results for Re-engining[a]

					Fuel Savings	
Re-engining Candidate (Aircraft/Engine)	Fleet Size	Annual Flight Hours	Change in Thrust (%)	Annual Fuel Used (million gal)	(%)	(million gal/yr)
C-130H/AE 2100[c]	272	117,776	N/A	169	28.0	47.3
C-130H/PW150[c]	272	117,776	N/A	169	25.0	42.3
B-1/F119/5.0	67	17,745	23	82	10.0	8.2
E-3/CFM56-2B-1	32	17,184	3	34	11.8	4.0
E-3/JT8D-219	32	17,184	0	34	6.2	2.1
E-3/CFM56-7B22	32	17,184	8	34	19.1	6.5
E-8/CFM56-2B-1[d]	19	8,704	–	–	–	–
E-8/JT8D-219[d]	19	8,704	–	–	–	–
E-8/CFM56-7B22[d]	19	8,704	–	–	–	–
KC-135D/E/CFM56-2B-1	115	35,190	20	45	15.8	7.1
KC-135D/E/JT8D-219	115	35,190	17	45	10.4	4.7
KC-135D/E/CFM56-7B22	115	35,190	26	45	22.7	10.2
B-52/F117-PW-100 [4]	76	24,016	19	71	24.7	17.5
B-52/CF34-10A [8]	76	24,016	9	71	15.9	11.3
B-52/CFM56-5C2 [4]	76	24,016	–9	71	26.6	18.9
C-5/CF6-80C2 (F103-GE-102)[e]	111	40,737	–	–	–	–

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the Avitas *BlueBook of Jet Engine Values 2007* or the *IBA Engine Value Book 2005*.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

TABLE 5-8 NPV Analysis Results for Engine Modification[a]

					Fuel Savings	
Engine Modification Candidate	Fleet Size	Annual Flight Hours	Change in Thrust (%)	Annual Fuel Used (million gal)	(%)	(million gal/yr)
KC-135 R/T/CFM56-2B-1 (Mod)	420	147,495	0	359	2.1	7.6
C-130H/T56-A427 Mod[c]	272	132,262	N/A	189	13.0	24.6
C-130H/T56-S3.5 Mod[c]	272	132,262	N/A	189	8.0	15.1
B-1/F101 Mod	67	23,356	0	109	10.0	10.9
KC-10/CF6-50 Mod	59	51,237	0	177	0.3	0.5

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the Avitas *BlueBook of Jet Engine Values 2007* or the *IBA Engine Value Book 2005*.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

Estimated Savings on Fleet Maintenance Cost		Cost (million 2006 $)		Years to Recoup[b] with Fuel Cost Annual Increase of			Cash Flow at 20-yr Point (million $)[b] with Annual Fuel Cost Increase of		
(%)	(million $/yr)	Production of One Engine	Total Development	3%	6%	9%	3%	6%	9%
50	14.1	1.3	45	17.7	14.4	12.4	203	817	1,715
50	14.1	1.2	95	19.5	15.5	13.2	37	585	1,387
11	7.5	5.2	26	>60	51.1	33.5	−1,029	−922	−767
59	13.9	2.3	52	22.2	19.0	16.6	−34	20	98
52	12.2	2.6	59	36.3	29.4	24.5	−157	−128	−87
72	17.0	2.4	53	16.5	14.5	13.0	78	165	291
–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–
53	24.4	2.2	52	45.1	32.3	25.4	−532	−438	−301
44	20.5	2.4	59	>60	47.9	34.3	−769	−707	−616
68	31.3	2.3	53	31.6	24.9	20.6	−378	−243	−46
45	25.6	2.8	81	20.6	17.0	14.6	−27	206	545
78	43.8	2.0	48	28.4	23.5	19.9	−361	−211	7
68	38.5	2.6	90	16.1	14.1	12.6	224	475	841
–	–	–	–	–	–	–	–	–	–

[c] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[d] E-8 re-engining already in progress.

[e] C-5 re-engining already in progress

Estimated Savings on Fleet Maintenance Cost		Cost (million 2006 $)		Years to Recoup[b] with Fuel Cost Annual Increase of			Cash Flow at 20-yr Point (million $)[b] with Annual Fuel Cost Increase of		
(%)	(million $/yr)	Production of One Engine	Total Development	3%	6%	9%	3%	6%	9%
12	14	1.0	15	>60	56.6	36.6	−1,318	−1,213	−1,060
40	11	0.7	60	17.8	14.6	12.6	107	431	905
40	11	0.7	60	26.1	19.7	16.3	−184	15	307
46	26	0.5	9	8.0	7.7	7.4	470	610	815
15	25	0.2	0	3.8	3.8	3.8	325	333	343

[b] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[c] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

TABLE 5-9 Sensitivity of Years to Recoup Investment to Total Burdened Fuel Cost[a]

Candidate Aircraft/ Engine Configuration	Years to Recoup Investment with Total Burdened Fuel Cost of				
	$2.50/Gal[b]	$5/Gal[b]	$10/Gal[b]	$20/Gal[b]	$40/Gal[b]
Re-engining					
C-130H/AE 2100[c]	17.7	10.9	7.3	4.2	2.5
C-130H/PW150[c]	19.5	11.7	7.9	4.8	3.1
B-1/F119/5.0	>60	55.7	24.4	12.9	7.8
E-3/CFM56-2B-1	22.2	15.7	10.5	7.2	5.2
E-3/JT8D-219	36.3	26.2	17.5	11.3	7.5
E-3/CFM56-7B22	16.5	11.6	8.0	5.7	4.0
E-8/CFM56-2B-1[d]	–	–	–	–	–
E-8/JT8D-219[d]	–	–	–	–	–
E-8/CFM56-7B22[d]	–	–	–	–	–
KC-135D/E/CFM56-2B-1	45.1	28.6	17.6	11.0	7.4
KC-135D/E/JT8D-219	>60	48.9	27.8	16.3	10.0
KC-135D/E/CFM56-7B22	31.6	20.9	13.5	8.8	6.2
B-52/F117-PW-100 [4]	20.6	13.2	8.7	6.1	3.9
B-52/CF34-10A [8]	28.4	20.0	13.3	8.9	6.3
B-52/CFM56-5C2 [4]	16.1	11.2	7.8	5.6	3.6
C-5/CF6-80C2 (F103-GE-102)[e]	–	–	–	–	–
Engine modification					
KC-135 R/T/CFM56-2B-1 Mod	>60	>60	30.0	15.9	9.5
C-130H/T56-A427 Mod[c]	17.8	11.1	7.6	4.6	3.1
C-130H/T56-S3.5 Mod[c]	26.1	15.3	9.9	6.6	4.1
B-1/F101 Mod	8.0	6.9	5.4	4.3	4.1
KC-10/CF6-50 Mod	3.8	3.6	3.3	3.0	3.0

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the Avitas *BlueBook of Jet Engine Values 2007* or the *IBA Engine Value Book 2005*.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[c] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[d] E-8 re-engining already in progress.

[e] C-5 re-engining already in progress

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6

Other Considerations

This chapter discusses additional factors that may lead to increased fuel efficiency, including aerodynamic modifications, optimization of operations, maintenance practices, operational practices, and aircraft weight management. It also covers benefits other than increased fuel efficiency of re-engining the large nonfighter aircraft fleet.

AERODYNAMIC MODIFICATIONS

This section discusses three areas—winglets, laminar flow nacelles, and airframe modifications unique to the C-130—where aerodynamic modifications may increase fuel efficiency in the large nonfighter aircraft fleet.

Winglets

As presented by the Air Force Scientific Advisory Board (AFSAB), aerodynamic improvements from wing retrofits such as winglets may improve fuel efficiency by as much as 7 percent over current performance (AFSAB, 2006; Karagozian, 2006). While this option is not necessarily feasible for all the large aircraft in this study, the potential exists for winglets to aid a large portion of the Air Force and DoD fleet. Industry has designed and installed winglets on the 737-700/800, 737-300, and 757-200 aircraft, and they have been designed and are available for installation on the 737-900, 767-300ER, 757-200, and 737-500; a winglet for the 777-200ER is in product development (Inman, 2006).

Demonstrated benefits of blended winglets installed on commercial aircraft include lower block fuel, lower emissions, improved takeoff performance, which leads to better initial cruise altitudes, reduced engine maintenance costs, and increased payload range capability (Lombardo, 2003; Inman, 2006). While there is not a direct mapping from the commercial aircraft listed above, some large Air Force aircraft are similar enough that benefits of winglets can be predicted, and the benefits are expected to be great.

The block fuel improvement per aircraft at the design range is between 4.0 and 4.9 percent for the

737-300/700/800 and 757-200 and is estimated at 5.7 percent for the 767-300ER. The resulting potential annual fuel savings per aircraft is 100,000-110,000 gal for the 737-300 and 737-700, respectively; 130,000-150,000 gal for the 737-800 and 737-900, respectively; up to 300,000 gal for the 757-200; and up to 500,000 gal for the 767-300ER (Inman, 2006).

According to Inman, "With over 1,080 commercial aircraft currently flying with blended winglets, commercial airlines are currently saving 107,700,000 gallons per year. . . . Assuming APB's projected delivery rate, by the end of 2010 blended winglets will have saved the commercial airlines approximately 2,000,000,000 gallons of fuel" (Inman, 2006).

Though this study is focused on fuel savings, blended winglets also reduce maintenance costs because the aircraft do not need as much thrust to achieve the same climb and cruise performance. In addition, blended winglets improve performance when operating in airfields that are at high altitudes and/or in hot environments and from airfields where operations are limited by obstacles or climb (Inman, 2006).

The uninstalled cost of blended winglets for the 737-700 and the 737-800 is $725,000 per kit. It is $850,000 per kit for the 757-200 and $1,500,000 per kit for the 767-300ER (Inman, 2006). Installation costs vary by aircraft but are not prohibitively high.

There is significant synergism between reductions in thrust-specific fuel consumption (TSFC) and aerodynamic improvements by means of increases in lift/drag (L/D) (Karagozian, 2006). The winglet modification increases L/D. This is shown in the Breguet range equation:

$$\text{Range} = \text{Velocity}/\text{TSFC} * (L/D) * \ln(1 + W_{\text{fuel}}/[W_{\text{pl}} + W_0])$$

where TSFC is fuel flow rate/thrust, W_{fuel} is fuel weight, W_{pl} is payload weight, and W_o is operating empty weight (OEW).

A 10 percent decrease in each of the three parameters—TSFC, L/D, and OEW—would result in a fuel savings of ~28 percent (Karagozian, 2006). While more specific analysis is required to determine which aircraft could be modified by adding winglets (including a structural analysis of the existing wing), it is possible to analytically determine the significance of installing winglets on some aircraft. The committee presents an example based on 417 KC-135R aircraft to make the point. The assumptions used in the example are as follows:

Kit cost:	$1.5 million per aircraft
Installation cost:	$1.0 million, $2.0 million, and $3.0 million per aircraft
Fuel used:	359 million gallons (FY96-FY05 average) for the fleet
Block fuel reduction:	4.9 percent (by analogy to the 767-300ER)
Fuel saved:	17.59 million gal/yr

The cost of modifying the KC-135R is not knowable until the wing loads and structure have been thoroughly studied. However, in 1981 there was a National Aeronautics and Space Administration (NASA) KC-135 winglet study (NASA, 1981a) accompanied by a flight test of winglets on a KC-135A in 1981 (NASA, 1981b). It was noted that parts of the wing probably needed to be strengthened. At this writing, the committee has insufficient knowledge of what wing modifications would be needed to make a precise calculation, so it parameterizes the modification cost to be $1 million, $2 million, and $3 million per aircraft. While this may or may not be an adequate representation of the modification cost, it illustrates the point. Another of the variables in this calculation is the cost per gallon of fuel. Figure 6-1 shows the relationship of payback period to cost of fuel per gallon for fuel saved and the modification cost per aircraft. The costs plotted here do not take into account NPV.

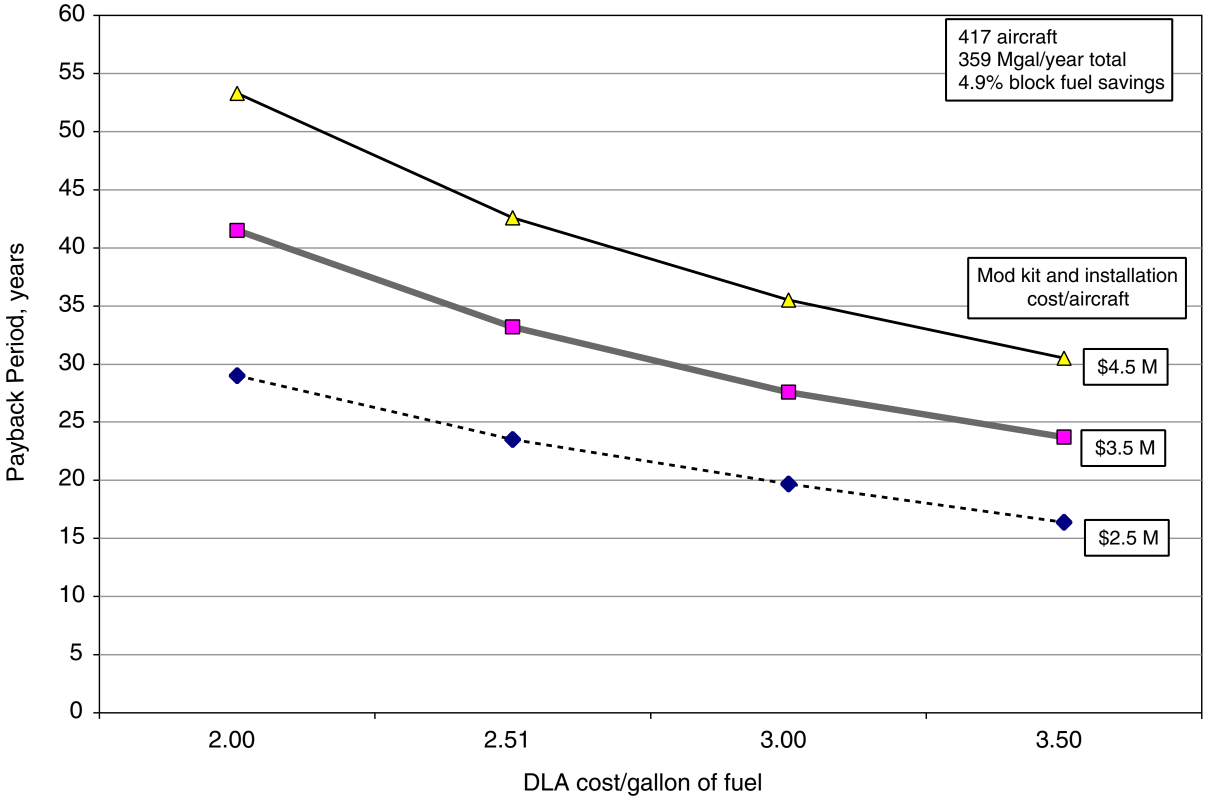


FIGURE 6-1 Winglet modification payback period vs. modification cost and cost of fuel. DLA, Defense Logistics Agency. SOURCE: Committee generated.

As can be seen in Figure 6-1, the more expensive the fuel the more cost-effective the modification can be, assuming that the Air Force can negotiate a reasonable cost for the winglet kit and modification. In this example, using $2.5 million as the modification cost per aircraft and the current cost of fuel ($2.51/gal), the payback period is 23.5 years. At $3.00/gal, the payback period is 19.7 yr, and at $3.50/gal, the payback period is 16.41 yr. If the modification cost plus the cost of the kit were $4.5 million per aircraft, the payback period would be correspondingly longer, as shown in Figure 6-1. In this specific example, at a replacement rate of 24 new aircraft per year, it would take the Air Force more than 17 yr to replace the 417 aircraft, and at 12 new aircraft per year, the time to replace would be 34.8 yr. Straightforward calculations such as these, along with an analysis of the wing itself, permit the decision maker to make an informed choice.

This simple example is not meant to minimize or oversimplify the engineering and cost analysis that goes into a decision like this. While there is a potential to save fuel—and, thereby, money—the costs of modifying an aircraft, particularly aircraft that are more than 40 years old, may be substantial. The only way to understand the potential benefit is to do the analysis, including the engineering analysis.

Finally, it may be that a greater good argument prevails and that the decision is made on more than economic grounds, in which case the controlling variable is saving fuel, not at any cost but at a reasonable cost.

> **Finding 6-1.** A deeper study of the use of winglets on Air Force nonfighter aircraft is warranted and will be carried out at a later date.

> **Finding 6-2.** The Air Force has no control over the cost of fuel. Money has to be spent to save fuel. The expected remaining life of a fleet of aircraft relative to the payback period determines if such a modification would be cost-effective.

> **Recommendation 6-1.** Operational suitability must be taken into account during both flight and ground operations. Once the engineering and operational suitability analyses have been done and the cost of modification (to include loss of aircraft availability) has been determined, the cost-effectiveness calculation is straightforward and must be considered for each type of aircraft as a function of remaining life. Because the Air Force has some control over how long it keeps a given fleet of aircraft, it can exert some leverage with respect to the modification cost per aircraft.

Laminar Flow Nacelles

Another opportunity for increasing L/D is through the use of laminar flow nacelles. The elimination of most of the turbulent skin friction drag on the nacelle reduces aircraft drag by approximately 1 percent.

The laminar flow technology for nacelles relies principally on shaping the outer nacelle profile so as to provide a long run of stable laminar flow over most of the length. Nacelles are short enough so that this can be readily accomplished. Further, the maximum outside diameter of the nacelle is not affected. The nacelle surface must be smooth and clean for this technology to work—no steps or gaps, however small. A number of studies also consider the use of suction, in addition to shaping, to make the laminarization more robust. This technology has been around for some time but has not so far been adopted into commercial aircraft operation.

Boeing is incorporating laminar flow nacelles into its 787 aircraft. This is done by having a smooth, continuous, single-color painted surface on the nacelle. Paint edges due to multiple colors would be enough to trip the boundary layer and must be avoided. This technology could best be incorporated into nonfighter aircraft by shaping alone, with smooth external surfaces (no suction). The nacelle surfaces would need to be cleaned frequently and monitored for surface defects.

Since there is no commercial experience with this technology, it is hard to estimate costs. Installation might require modifying the engine mount to accommodate the altered external shape of the nacelle, modestly increasing the maintenance cost. But the possibility of a 1 percent reduction in drag would justify consideration of this technology in re-engining.

> **Recommendation 6-2.** Laminar flow nacelles should be considered as an option when re-engining aircraft that have pod-mounted nacelles.

Airframe Modifications for Fuel Savings Unique to the C-130

Several modifications could result in fuel savings. The first is trimming the ailerons to redistribute wing loading in cruise condition (the original purpose was to reduce the bending moment at the wing root and provide an improvement in wing spar life). An unanticipated side benefit was found to be a significant reduction in drag at cruise. For example, with a –8 degree up-rigging of the ailerons, the drag reduction in cruise would reduce fuel consumption about 1.3 percent.

The addition of aerodynamic strakes at the rear of the aircraft has also been shown to reduce drag. In this case the improvement in fuel consumption was about 3.2 percent, but together the two modifications should improve fuel consumption about 4.5 percent for a modest investment. Lockheed also suggested that significant drag reductions might be possible through careful attention to and reconfiguration of the defensive measures and avionics devices that have been added to the aircraft in recent years. It gave as an example an antimissile device installed external to the airframe, significantly increasing drag (O'Banion, 2006).

Finding 6-3. Relatively simple and inexpensive devices can significantly reduce drag, with concomitant improvements in fuel consumption.

Finding 6-4. Airframe modifications for devices such as weapons racks, sensors, and electronic countermeasure (ECM) systems can increase fuel consumption if the potential for increased drag is not considered prior to installation.

Recommendation 6-3. The Air Force should conduct a detailed study to evaluate the potential for fuel savings from aileron up-rigging and strake modifications on the C-130. Aileron up-rigging may also be of benefit on other aircraft in the fleet, and a computational fluid dynamics study should be initiated to evaluate the potential for this modification.

Recommendation 6-4. Airframe modifications for devices such as weapons racks, sensors, and ECM systems should be evaluated with respect to their potential for increasing drag and fuel consumption. The fastest and cheapest way may not be the best way when all factors are considered.

OPTIMIZATION OF OPERATIONS

Commercial airlines have been able to reap significant cost savings by optimizing their planning and operations. For example, United Parcel Service management credits an optimization-based planning system for its aircraft network with having identified operational changes that had saved more than $87 million as of 2003, and it is anticipating additional savings of $189 million through 2014 (Armacost et al., 2004). Likewise, fractional aircraft operators, despite the probabilistic nature of business passenger demand, reap significant benefits by optimizing their operations. Indeed, the stochastic nature of business passenger demand is in many ways similar to that of military operations during a conflict, thus pointing to the applicability of optimization to the real-time replanning that is characteristic of wartime operations.

For monthly planning and real-time replanning, decisions are typically made by the planners and operators without advanced decision support. However, they do have access to comprehensive data systems. This situation is similar to the situation that existed at commercial airlines in the early 1990s. Based on the significant financial impact of schedule irregularities caused by weather—snowstorms, hurricanes, etc.—airlines have partnered with information technology firms to develop state-of-the-art decision support systems that assist their controllers in making tactical decisions about operations. Most of the concepts behind these systems are an outgrowth of academic research done in the late 1980s and early 1990s at the Massachusetts Institute of Technology (Clarke, 1997), the Georgia Institute of Technology (Lettovsky, 1997), and the University of Texas at Austin (Bard et al., 2001).

In the last decade, airlines have come to appreciate the value of centralized decision making across multiple disciplines that pertain to their operations. By moving to a centralized operations center, each operational department within the airline is better able to understand and appreciate the impact of its decisions on downstream decisions and dependent activities. The development of the airline operations control center and the introduction of real-time decision support systems have enabled airlines to minimize flight cancellations and delays and ultimately improve operating profits (Clarke et al., 2000). For example, Continental Airlines was awarded the 2002 Franz Edelman Award for Achievement in Operations Research for the implementation of CrewSolver (developed by Caleb Technologies), which was reported to have saved $40 million in recovery costs in 2002, most of it attributable to its post-September 11 performance (Yu et al., 2003).

For more operational/tactical planning and execution, Air Mobility Command (AMC) has a division known as the Tanker Airlift Control Center (TACC). Here, much of the work is done manually (Nielsen, 2002). Some optimization work was done in the late 1980s and early 1990s using a system developed by Oak Ridge National Laboratories (ORNL), called Airlift Deployment Analysis System (ADANS) (Harrison et al., 1991). It used some optimization methods (mostly heuristic) and reported success in its work in support of the first Gulf War (ORNL, 2006). Components of ADANS were built into the Consolidated Air Mobility Planning System (CAMPS), which is currently in use at TACC. The planners, however, do not use the planning functions of CAMPS; instead, they use the system to manage data but make decisions based on experience and intuition (Nielsen, 2002).

A recent Broad Agency Announcement from the Air Force Research Laboratory (AFRL) seems to be a move in the right direction. It calls for the development of optimization methods that could be included in future versions of the AMC decision/data tools, such as CAMPS and the Global Decision Support System. However, recent work by Koepke on real-time execution and replanning (Koepke, 2004) has not been implemented.

Finding 6-5a. The commercial airline industry has reaped significant benefits from the introduction of optimization in both its planning processes and its daily operations.

Finding 6-5b. While the Air Force has implemented some optimization in its planning processes, it appears that the commercial airline industry has done so to a greater extent, especially in its daily operations, resulting in significant cost savings.

Conclusion 6-1. Optimization of Air Force operations could reduce the fuel consumption of nonfighter operations and should therefore be aggressively pursued.

Recommendation 6-5. The Air Force should study optimization and, where it has already done so, accelerate the implementation of optimization in all aspects of its operations, especially as it relates to maintenance and overhaul and to the scheduling of its cargo, passenger, and tanker fleets.

MAINTENANCE PRACTICES

There are several fundamental ideas that are critical to the understanding of the maintenance process. First, maintenance is a restorative process that at best returns the deteriorated equipment to its original design specifications. It cannot improve on the inherent capability, which is designed into the equipment. However, the maintenance process can identify design deficiencies. It can also be a good time to incorporate design changes to correct flaws and shortcomings. It is important to recognize that once the design is modified the maintenance process must be reviewed to see if it is still applicable and effective. Second, today maintenance is less about turning a wrench than about gathering information on the equipment and how it operates. Too often, however, this information is not collected, not understood, or not taken advantage of to correct deficiencies and improve the maintenance process.

Maintenance evolved primarily from practical hands-on experience. If something failed, you either repaired or redesigned it. It depended in the earlier stages mostly on the knowledge of the maintainer and his or her skills. It tended to be reactive rather than proactive. Analysis of the maintenance skills and processes lagged behind analysis of the design process. Now, however, with the growing complexity of the new equipment and the burgeoning cost of operating it, maintenance has become more dependent on data and less dependent on the skills of craftsmen. It is being driven by information systems that better analyze trend data and by better information about the inherent operating characteristics of the equipment through better sensor technology and real-time diagnosis.

Unfortunately, quite often this new knowledge is not well transmitted to the people who touch the equipment and whose hands-on experience prevails over available diagnostic and analytical tools. This conflict often clouds longer-term solutions and allows deterioration beyond the obvious. Performance deterioration that occurs over longer periods of time may not get the same attention if the failure is not obvious.

Consequently, over the years some of the more obvious deficiencies, such as mechanical failures or structural problems, are cured at the expense of the more subtle deterioration caused by aerodynamic anomalies or small and not so obvious deteriorations of seals, clearances, etc. The human eye is still the primary driver of the restorative process. The closer the maintainer is to the equipment, the more effective the maintenance.

There certainly are more and more tools available, but they have not changed the maintenance process nearly as much as they have improved equipment reliability. Maintenance has lagged both culturally (in terms of the acceptance of change) and technically (in terms of the use of information technology to identify systemic trends).

However all is not hopelessly slow, and change is indeed taking place. On-wing condition and failures are being bound together in a holistic approach, whereby maintenance shops and maintenance on the line and away from the shops and the actual operating events are being slowly tied together. As the maintenance process evolves, it becomes easier to track more subtle deterioration such as fuel burn and aerodynamic degradation and not just pending mechanical failures.

To maintain engines at their optimal efficiency, new strategies of maintenance must be undertaken. Of note, however, none of these strategies will produce optimal results by themselves; they are intrinsically tied together.

The first consideration in any policy regarding engine maintenance is that fuel savings and good fuel consumption are generally not the primary focus of maintenance but are the result of building an engine to a standard as close to the optimal design limits as possible. Engines built to higher standards tend to be more efficient and may have higher maintenance costs up front; however, these costs are spread over the life of the equipment. This is not an insignificant issue in determining build standards. Too often the cognizant authority will build engines to a low-cost standard from a shop visit standpoint, saving short-term costs. This may not be the most economical build from the standpoint of life-cycle costs (LCCs). It is critical that the objectives of the shop and the objectives of total cost are aligned. Engine shops have a great deal of flexibility to exercise economic judgments, which may have longer term consequences to transfer cost to other areas. There are numerous examples where shortsighted build standards lead to short time on the wing, high fuel consumption, etc. It is critical that the build standards are developed with the objective of minimizing LCC, not just obtaining parochial benefits.

The second consideration for fuel efficiency is that the engine is only one part of an integrated airplane system. Thus to create a high standard in the shops but install these engines on only deteriorated airframes negates some of the benefits. Thus, the maintenance policy regarding fuel consumption must be developed for the aircraft as well as the engine.

The third element of the strategy is to gain a comprehensive knowledge of the condition of the equipment. This involves information systems that track not only operational data but also data on shop and build. Necessary information elements include aircraft fuel burn, engine build standards, and work performed in the shop and on the line. This information, too, must be viewable from a holistic not just a parochial perspective such as the engine shop or on the line. This requirement for data that will allow understanding fuel consumption and its dynamics means there must be an organizational structure and data systems in place that can track both on- and off-aircraft information and determine build standards and other actions involving the aircraft. These systems must be in a position to affect the outcome of maintenance. Rarely is there a global or comprehensive information network that captures all the relevant data or an integrated organizational structure that can analyze the available data.

This then leads into a discussion of strategies for maintenance and some understanding of what it takes to both manage the mechanical condition of the equipment and optimize its performance.

On-Wing Programs

On-wing programs require (1) an understanding of the various conditions of the aircraft that can cause mechanical malfunction and operational deterioration; (2) a history of the maintenance that was done; and (3), most importantly, a set of measures and procedures for efficient operation of the equipment.

The following discussion includes some of the strategies that might be able to assure better fuel burn of the air and engine system.

Mechanical Condition of the Aircraft

A program must be developed that takes into account some of the systems that if not operating properly can adversely impact fuel burn. Some engine instrumentation, such as instruments measuring engine pressure ratio, requires accurate air data. Often pneumatic leaks can cause a misleading reading in aircraft not being flown correctly. Leaks are common on older aircraft, and slight anomalies in engine indications can cause significant power differences between engines. This, in turn, causes deviations from optimal operating conditions and often leads to excessive trimming and, in some cases, subtle flight control deflections, which can adversely impact fuel burn. Instrumentation, especially with air-driven instruments, is one of the primary causes of excessive fuel burn.

Aircraft Pressurization System

Good maintenance here can prevent unnecessary fuel burn. Making sure that the aircraft is not leaking is very important, and programs to assure that the aircraft is properly sealed will yield significant benefits:

- *Seals.* While aerodynamic cleanliness often keeps maintainers busy with little payback, there are some areas where paying attention can and does have significant benefits in fuel savings. Making sure that seals between the lower and upper wing are in good condition, especially on the leading edges, is one such area.

- *Flight controls.* It is imperative that flight controls are properly rigged. Floating spoilers, flaps that are not properly seated, ailerons not properly rigged—all can have a very large impact on fuel burn. Large surfaces such as rudders are especially critical, and not only if they are out of rig but also if the engines are not producing symmetrical thrust, they can cause excessive fuel burn.
- *Good housekeeping.* Simple actions such as keeping the leading edges clean and free of excessive dents and making sure the pitot static line is free of bugs and obstructions can have large benefits. Occasional washing of the aircraft, weighing of the aircraft, and, of course, engine wash all lead to better operations and in some cases significantly reduced fuel burn.
- *Engine wash.* Engine water wash has been used successfully by commercial airlines for many years routinely to restore exhaust gas temperature margins and, in some cases, improve engine performance, including fuel burn. It is a standard practice that has proved to be effective and is recommended by the engine manufacturers as well. This is a very economical process that has great benefits for very little effort. If no such wash program exists, the committee recommends that one be introduced for the entire Air Force engine inventory.

Engine Maintenance Programs

Once the engine is in the shop, restoring its proper operating parameters is the goal. However this generally focuses most on what caused the engine to be removed, what can bring it back into specification, and its obvious faults and failures. Consequently, programs need to be put in place where there is sufficient knowledge about the condition of the engine, relationship of fuel burn deterioration versus time, and the modification levels available to assure good operating parameters.

As mentioned above, the key to engine maintenance in the shop is in-depth systems for gathering and analyzing the data that identify those deficiencies, the frequency of occurrence, and their relationship to other repair requirements so that a build standard can be developed not only to repair obvious failures but also to restore efficiency. A competent engineering staff that can dictate restoration requirements and a rigorous data system that provides the necessary information before and after repair are critical to this effort.

SFC and fuel burn information are critical data inputs for repair. In addition, certain parts of the engine that have a greater impact on fuel burn—e.g., compressors—may be applicable. Finally, ensuring that engine externals, such as bleeds, perform to specification may further benefit fuel consumption.

Information, Data Requirements, and Organizational Structure

Historically, engine data tended to be controlled vertically in functional areas. Too often, the shop and the line did not cross-feed information. Also too often, the expertise that resided in the shop did not have access to line operations personnel to advise them. This is not peculiar to the military, but it is exacerbated by the different contractors, locations, and the like that characterize the military. In the commercial sector there is a much closer tie to operations on the part of both line and shops. Since military aircraft are not designed for the same missions as commercial aircraft, the information challenges are much more critical.

Napoleon's army marched on its stomach but the maintenance army marches on information. To fully benefit from the maintenance actions and processes it is essential that information systems are available that give holistic views of aircraft fuel consumption, engine SFC, component reliability, maintenance schedules, reliability, maintenance actions, and histories of faults and failures of the various systems and components that make up the power plant–aircraft interface and that have an impact on fuel consumption.

While this study does not formally address information system requirements, those requirements must nonetheless be recognized as an essential element in achieving progress with fuel consumption. Lastly, the maintenance entity must be organized along the flow of information to assure that there is top-down and bottom-up access to all the knowledge that is needed to maintain the equipment. This knowledge cannot be isolated to functional areas. At the end of the information trail, there must be an organizational function that makes decisions across all the disciplines in a holistic fashion to ensure the greatest efficiency.

> **Finding 6-6.** The creation of an integrated maintenance database, drawing from the military and civilian sectors in cases where common engine variants are used by both, is critical to achieving operational fuel efficiency. The commercial sector is a particularly good source of operating data because it experiences much higher utilization rates. The military can often gain insight, at no cost, on future problems and remedies.
>
> **Recommendation 6-6.** The Air Force should undertake a review of maintenance requirements and how they affect fuel efficiency and/or fuel conservation. Additionally, it should have in place an organizational structure that will have the focus and authority to establish maintenance requirements across all operations. Additionally, the Air Force should undertake a comprehensive review of information systems to assure that repair histories and reliability information are being utilized in a holistic manner and being transmitted to the appropriate organizations—that is, those that have oversight responsibility for efficient operations and the ability to implement the required actions. Critical to this recommendation is the establishment of fleet manager programs to oversee the entire maintenance operation, both line and shop, and the development of a comprehensive information system to monitor the effectiveness of maintenance actions and fleet performance. The ability of an integrated database to inform a cognizant organization that has a say about the outcome of maintenance, whether in the field or in the shop, is a critical factor in achieving operational fuel efficiency. Lastly, the maintenance entity must be organized along the flow of information to assure that there is top-down and bottom-up access to all the information that is required to maintain the equipment.

OPERATIONAL PRACTICES

Operational practices affect fuel consumption. For example, aircraft configuration during taxi can affect fuel consumption. So can the use of an auxiliary power unit (APU) for power rather than ground power, chosen flight routes, training policies, etc.

Examples of actions the Air Force could take to reduce fuel consumption include the following:

- Ensure flight planning is based on both operational requirements and optimal fuel burn requirements.
- Use ground power where possible. Start tracking APU usage hours. Standard commercial practice is to assign an aircraft a parking spot upon landing and, if ground power is available at that location, not start the APU. Standard Air Force practice is to start APUs upon landing.
- Taxi with as few engines as possible. Ensure that engine start and warm-up procedures, as well as shutdown and cooldown procedures, are in effect. Standard commercial practice is to start

engines when ready for takeoff. Standard Air Force practice on many aircraft, like the KC-135, is to start engines 30 min before takeoff.

- Use available technology to analyze wind patterns and allow pilots to save fuel by flying at preferred altitudes and speeds, leveraging tailwinds and avoiding headwinds when possible.
- Instill more scheduling discipline. Tankers frequently schedule a mission to refuel a given number of aircraft and end up refueling a different number. If scheduled refueling is canceled, the tanker is carrying extra fuel. Since aircraft in the area occasionally take advantage of a tanker's availability, tankers often carry more than scheduled offload quantities of fuel.
- Only fly the flying hours required to accomplish mission requirements. Air Force flight plans often call for fixed mission durations. Even if mission requirements are met using less than the scheduled flying time, aircraft often fly navigation or transition legs to use up the remaining flying hours. Change the headquarters and operational command cultures that grade units with metrics like flying all of the yearly flying hour allocation vs. meeting mission requirements and rewarding those units that meet mission requirements using fewer flying hours.
- Review requirements that dictate reflying a functional check flight (FCF) for an aircraft coming out of program depot maintenance after the aircraft does not pass the FCF because a single system has failed. Conduct analysis to determine if some or most FCF refly can be eliminated by use of expanded ground or bench testing of failed systems.
- Make sure pitot static tubes are clear and leading edges clean.
- Ground ship equipment/supplies as much as possible.
- Use ground power to heat and run electrical systems whenever possible.

Finding 6-6. Reduced maintenance costs and improved operational performance can have a significant impact on the benefits resulting from re-engining or engine upgrades. The preceding discussion notwithstanding, the Air Force is committed to quality and has adopted elements of six sigma, lean, and other quality principles in its practices and procedures. In addition, many of the companies that supply engines, parts, and components to the Air Force employ six sigma in their processes.

AIRCRAFT WEIGHT MANAGEMENT

The fuel consumption of an aircraft is primarily dependent on lift, drag, and weight. How closely, though, does the Air Force pay attention to the weight of the aircraft once it is put in service? Does the Air Force really know what the aircraft weighs? Does it really know what the cargo weighs? Does it really know how aircraft fuel consumption is affected by the weight of extra fuel carried onboard?

There are actions the Air Force could take in the near term that could positively affect fuel consumption, among them the following:

- Establish a baseline of what is routinely carried on the aircraft (pallets, tools, etc.). Obtain fleet aircraft weight samples to determine the spread in actual weights, including by weighing some operational aircraft ready to go out on a mission and some empty aircraft. Weigh all the equipment that is put on aircraft such as repair kits, etc. Weigh all cargo; do not use estimated weights.
- Revise operational practices to reduce unnecessary weight. For training flights, ensure aircraft are not carrying any equipment that is not part of the mission. Do not carry excess fuel since its weight increases fuel consumption. Review the need to carry remote station tools and equipment and make sure of their weight. Weigh all cargo until it becomes certain that the typical weights are accurate.

- Revise maintenance practices to reduce unnecessary weight. Ensure aircraft are clean and not carrying lots of trash and dirt. Check insulation blankets for condensation, which can increase the weight of the blankets significantly—for example, the blankets for a 707 weigh more than 1,000 lb. Consider substituting lighter weight materials in floor panels, etc. (floors in KC-135s, for example, are made of plywood). Establish a maintenance weight program executive officer or equivalent.

The above are just a few examples (there are probably many more) of actions the Air Force could take in the near term to significantly reduce Air Force fuel consumption. One airline executive claims such actions saved his airline more than 100 million gallons of fuel last year against a 2004 baseline.

OTHER BENEFITS OF RE-ENGINING

Operational Benefits

The operational benefits and impacts of any given modification divide naturally into two categories:

- Internal mission improvements, which result in directly calculable fuel savings on the same mission profile, and
- Basing accessibility impacts, which can be translated into greater equivalent capability.

The operational benefits in the first category, "Internal mission improvements . . . same mission profile," consist of shorter time to climb and an increase in cruising altitude. Reduced time to climb and increase in cruising altitude both translate directly into fuel savings (assuming the output demanded by the missions is constant). Savings from both were folded directly into the return on investments calculations.

It is less clear that the operational benefits from improved wartime basing can be reliably priced. Nevertheless, such operational benefits can be quite substantial, although the quantification is in terms of increased wartime capability rather than of dollars saved, as would be calculated in peacetime (see discussion above on force structure trades).

To illustrate the operational benefits from improved wartime basing, consider the distribution of bases and runways in three illustrative scenarios, which may be taken as typical of operations worldwide. Figures 6-2 to 6-4, provided by RAND, show availability of runways within a given distance of the designated point in nautical miles (nm) for these scenarios using the following rules:

- At least one runway is operational.
- Runways made of gravel or sand are not considered.
- Runways must be in fair or better condition.
- A runway is deemed suitable if it can support a C-17 or KC-135R taking off at 50 percent of maximum fuel load.
- Maximum on ground, instrument flight rules, and other criteria are not considered.
- Runway strength requirements are moderate.

To properly interpret these charts to determine the operational benefits of improved wartime basing, it is important to understand the following:

- Each 500 nm increment to and from a given location is worth about 2 hr flying time, which can be a significant fraction of the total mission duration (they range from 5 to 20 hr, depending on

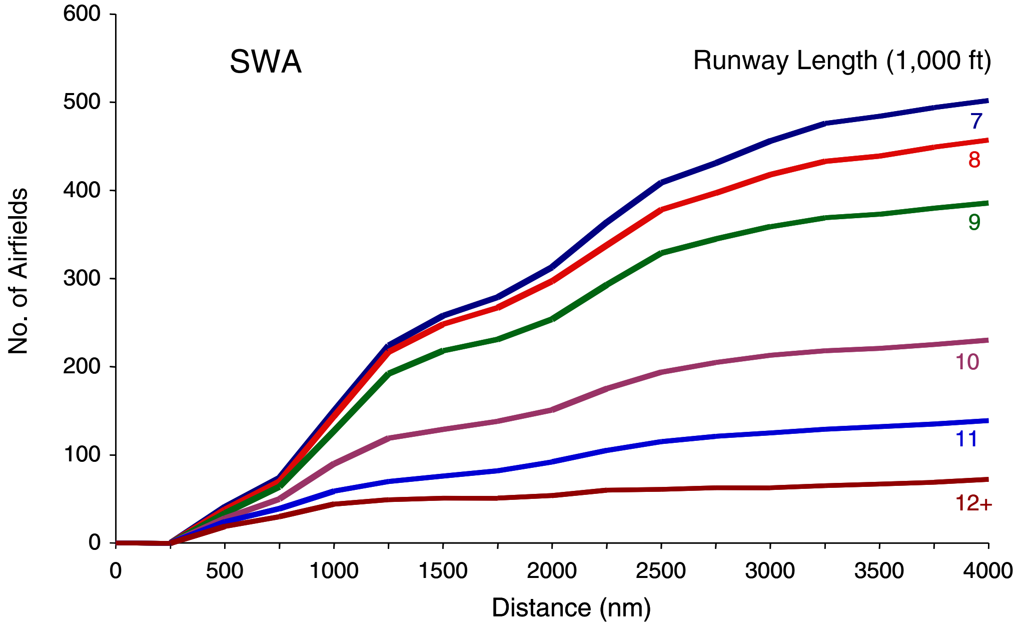


FIGURE 6-2 Scenario 1—Southwest Asia. SOURCE: RAND.

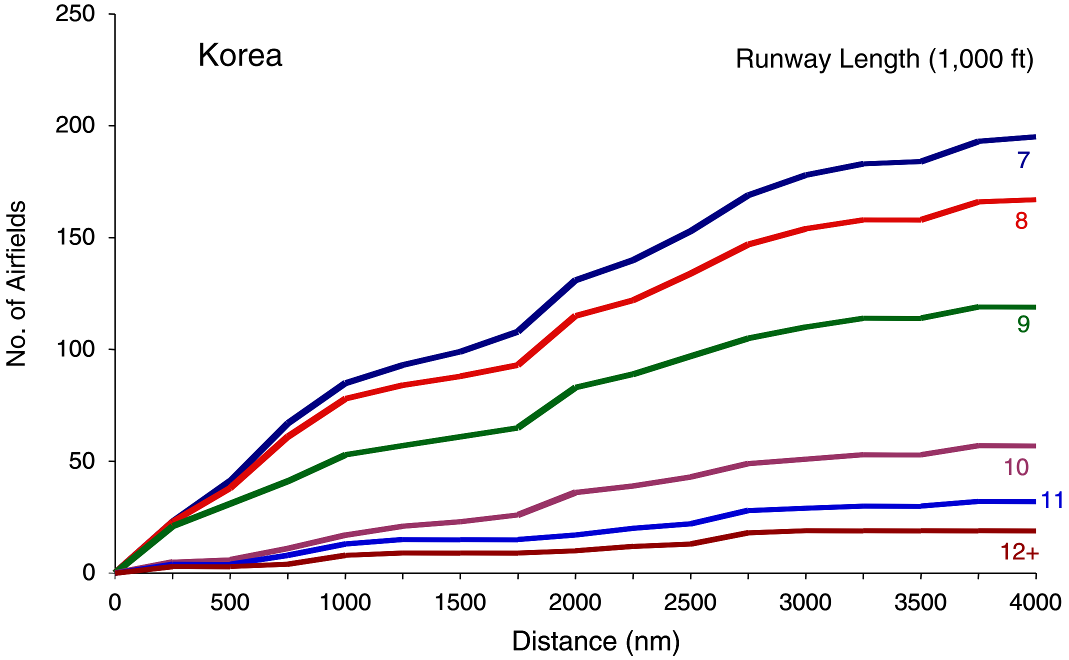


FIGURE 6-3 Scenario 2—Korea. SOURCE: RAND.

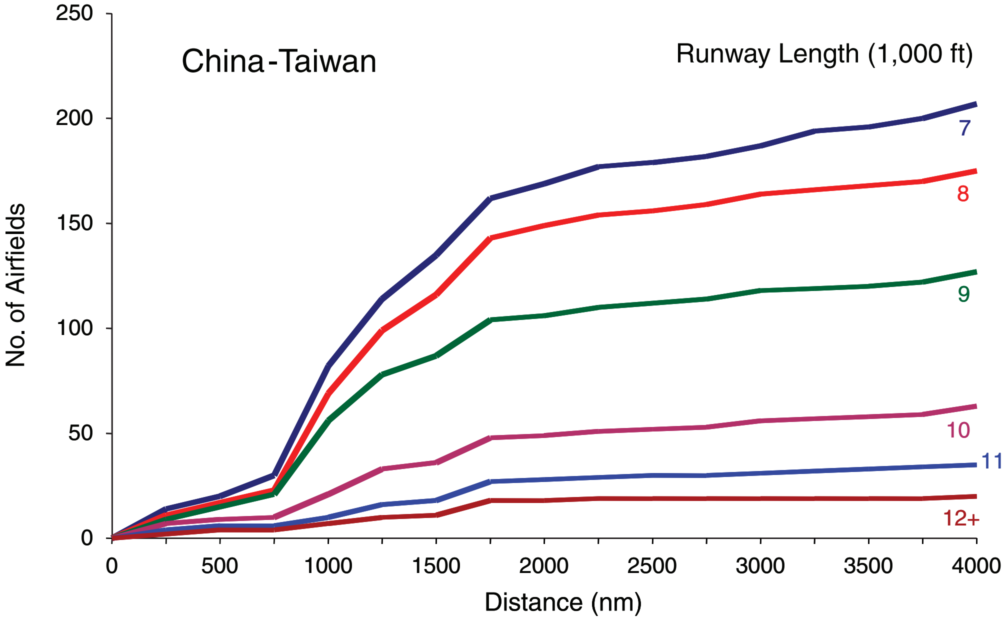


FIGURE 6-4 Scenario 3—China-Taiwan. SOURCE: RAND.

the mission). Hence, each 500 nm increment in improved basing might provide the equivalent of 10-40 percent more on-station time, or less refueling needed for the same station time, or more refueling capability, etc.

- Because of the double transit time, bases more than 1,000 nm from the operating location (Combat Air Patrol point, refueling track, etc.) get less useful very fast, and operations beyond 1,500 nm consume enormous resources compared to the same operations from, say, 500 nm away.
- While it might at first appear that there are many bases to be had, that perception is quite incorrect. U.S. uses of suitable bases must be negotiated in the run-up to the conflict or, worse, during the conflict. Such negotiations are generally difficult. The more bases available that are operationally suitable, the easier such negotiations get.
- Runway lengths tend to group themselves into three major categories: (1) long (>10,000 ft), typically needed by heavily loaded aircraft equipped with older, low-thrust (generally lower-bypass-ratio) engines, (2) medium (7,000-9,000 ft), suitable for moderately loaded and often even heavily loaded aircraft equipped with modern, higher thrust (generally higher-bypass-ratio) engines, and (3) short (<6,000 ft), suitable for aircraft that are generally designed for such operations (like C-17 and C-130 aircraft).
- Modifications that result in significantly higher installed thrust for the aircraft often allow the aircraft to operate on medium-length runways under the same operational safety rules that previously required long runways.
- The ratio of number of medium to long runways in the important range of 250 to 1,000 nm from typical operating locations ranges from ~3 to ~7.

Consider the case where a fleet of U.S. aircraft can use medium-length runways. If that same fleet could only use long runways, U.S. negotiators would have only 1/3 to 1/7 as many available with which to negotiate the bed down. Put another way, to secure the same number of long runways in the mix as available medium-length runways at ~500 nm, one can see from the above charts that the bed down planning horizon would have to expand out from ~1,000 to (in some cases, such as Korea) well over 2,500 nm, and while operations at the latter ranges are not impossible, they are difficult and absorb enormous resources. This is, to say the least, important.

Environmental Considerations and Implications

The impact of aircraft on environmental pollution (noise, emissions) is increasing. While nitrogen oxide (NO_x) emissions from aircraft account for only about 3 percent of the total tonnage of the NO_x emitted around the world and are therefore relatively small, they are forecast to become significant if nothing is done to regulate them. The commercial world has done this. Noise and emissions regulations of increasing stringency have been passed through the years. The Federal Acquisition Regulation (FAR) 36, Stage 3, regulation was passed in the United States in the late 1960s. It has since been updated and called Stage 4 (10 EPNdB cum tougher).

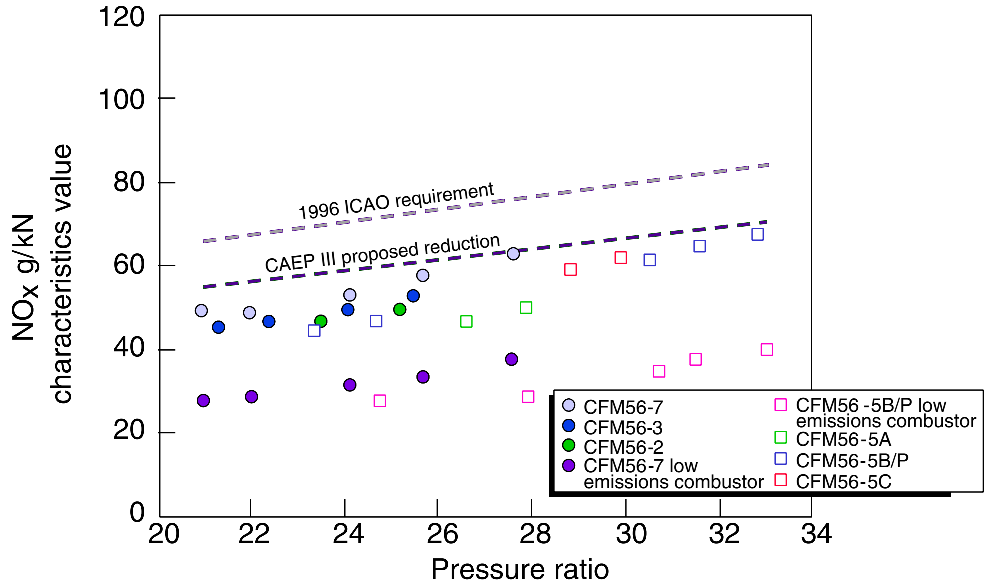
These strong U.S. regulations have been mirrored internationally by Annex 16 of the International Civil Aviation Organization (ICAO). Similar regulations for NO_x and other pollutants have been passed by ICAO and are enforced internationally.

Carbon dioxide (CO_2) is a harmful pollutant in terms of global warming. It affects the ozone levels in the atmosphere, global warming, and climate change (NRC, 2001). CO_2 emissions are directly related to fuel consumption, so that any fuel efficiency improvements directly reduce global warming. Particulate, hydrocarbon, and sulfur emissions are also of some concern and should be taken into consideration.

Environmental factors need to be considered in the selection of engines. Aircraft noise and engine emissions bring increasing penalties when U.S. military aircraft are operated in some other countries. In the United States, environmental regulations are being waived for military operations, but this could change overnight, and the Air Force needs to be prepared for their reinstitution, especially on tanker and transport aircraft.

It is important therefore that any re-engining opportunities address environmental constraints. The CFM56 engine family meets the current NO_x regulation, as shown in Figure 6-5. The dramatic noise reduction provided by the incorporation of the CFM56-2 (F108) on the KC-135 R is shown in Figures 6-6 and 6-7. The CFM56-2 powering the KC-135R airplane meets the FAR 36, Stage 3, regulations. A reduction in fuel consumption will also result in a reduction in CO_2 emissions.

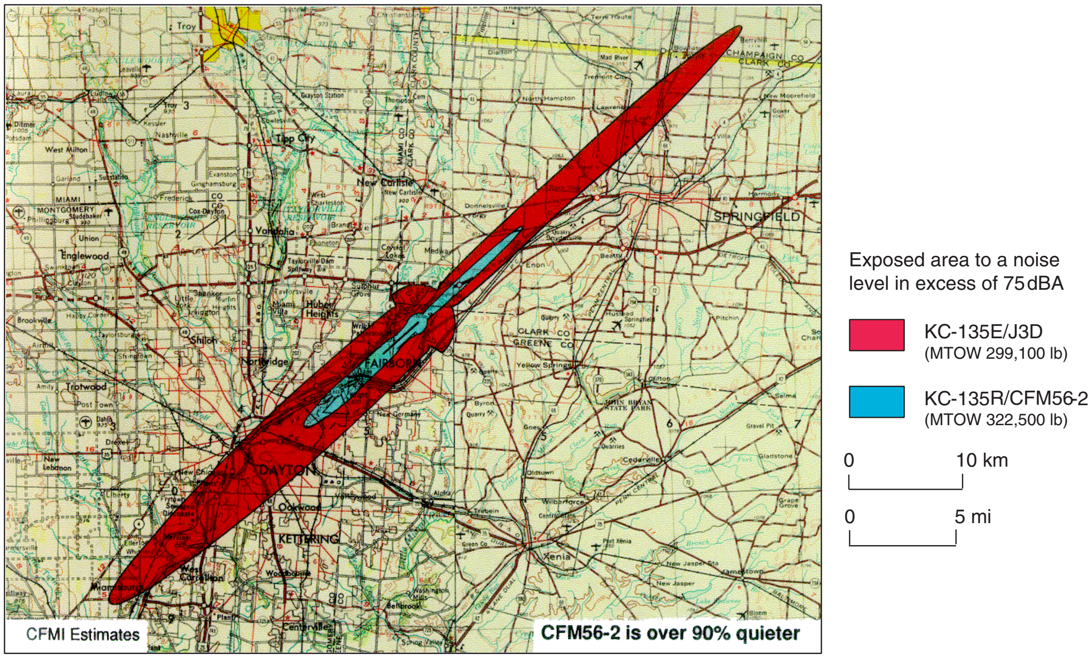
> **Recommendation 6-7.** Any re-engineering decision of the Air Force should take into account the back-to-back evaluations on a platform—for example, the B-52H, E-8, and E-3—of the different engine options in terms of noise and pollution. In addition, platforms should be environmentally acceptable for a significant amount of time into the future.



NO_x is 80% of All Aircraft Engine Pollutants*

*Based on a twin engine aircraft 500 nmi mission

FIGURE 6-5 CFM56 environmental NO_x emissions. SOURCE: CFM.



KC-135R with CFM56-2 engines is the world's quietest jet tanker

FIGURE 6-6 Actual noise disturbance over Fairborn, Ohio. SOURCE: CFM.

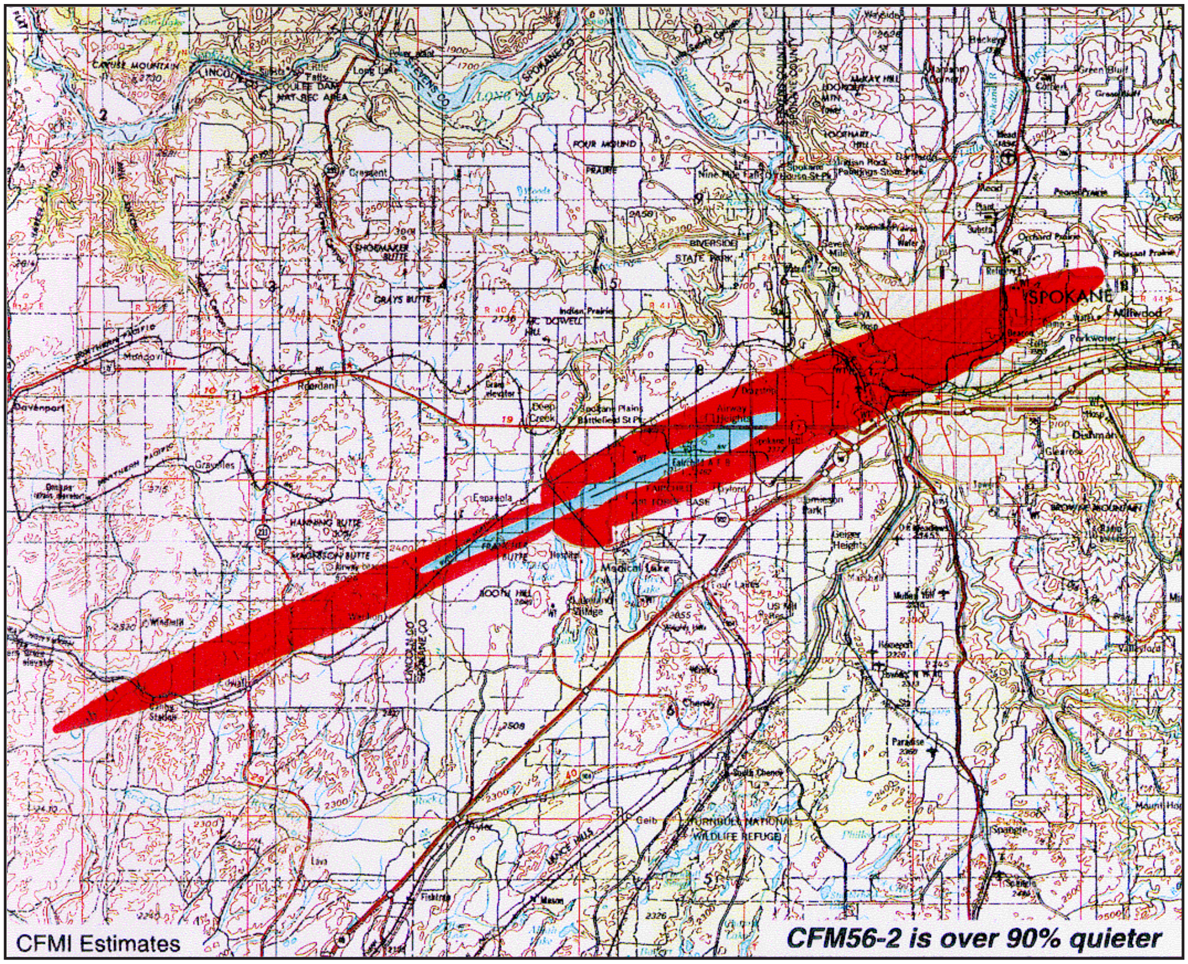


FIGURE 6-7 Actual noise disturbance over Fairchild Air Force Base. SOURCE: CFM.

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7

Alternative Fuels

BACKGROUND

> America is addicted to oil, which is often imported from unstable parts of the world. The way to break this addiction is through technology. . . . New technologies will help us reach another great goal: to replace more than 75 percent of our oil imports from the Middle East by 2025.
>
> President George W. Bush
> January 31, 2006
> State of the Union Address

Our nation's dependence on imported oil leaves it dangerously vulnerable to attack. A single well-designed attack on the petroleum infrastructure in the Middle East could send oil to well over $100 per barrel and devastate the world's economy. Schultz and Woolsey (2005) analyzed this vulnerability in a paper entitled "The petroleum bomb." As shown in Figure 1-1, the U.S. dependency on foreign oil is expected grow to 70 percent by 2025, and Figure 1-3 shows that the nonfighter aircraft in the Air Force inventory consume 69.9 percent (approximately 1.82 billion gal/yr) of DoD aviation fuel. From mid-2004 to mid-2006, the cost of jet fuel increased from approximately $1/gal to $2.53/gal, a significant extra cost burden. These two key factors led to the creation of the Assured Fuels Initiative in the Office of the Secretary of Defense (OSD). The initiative has the following mission:

> to catalyze the commercial industry to produce clean liquid fuels for the military from secure domestic resources using environmentally sensitive processes to enable a bridge to the future. (Sega, 2006)

DoD and the Department of Energy (DOE) are working jointly to develop national initiatives to produce, test, certify, and use alternative, or synthetic, jet fuel. On May 30, 2006, the *Commerce Business Daily* reported that the Defense Energy Support Center (DESC) was seeking industry proposals to supply 200 million gallons of alternative, or synthetic, Fischer-Tropsch (FT) fuel for the Air Force and Navy to conduct major vehicle and vessel field tests in 2008-2009 as part of a broader effort to reduce dependence on foreign oil and greenhouse gas emissions.

Specifically, the DESC request for information (RFI) seeks to identify potential suppliers of synthetic fuel for aviation that meets the FT draft synthetic fuel specification for delivery to various Air Force and Navy installations for multiple weapon systems testing and subsequent use. DoD is investigating the feasibility of supplying aviation synthetic fuel requirements of up to 200 million U.S. gallons, or any portion thereof, during calendar year 2008, with 100 million gallons meeting the JP-8 flashpoint of 38°C and 100 million gallons meeting the JP-5 flashpoint of 60°C. Further, DoD is interested in long-term prospects for the manufacture and supply of aviation synthetic fuels in increasing quantities, with an emphasis on domestic industrial capability and feedstocks. This request is an essential step in determining market interest in the manufacture and supply of aviation synthetic fuel. Interested parties have been asked to provide the following information: (1) ability to meet the draft specification; (2) current and future yearly production capability in the continental United States (CONUS) and outside the continental United States (OCONUS); (3) location of the production facility; (4) quantity that can be produced and when it can be made available; (5) type and location of feedstocks to be used in the production of aviation synthetic fuel; (6) capability and experience in the sale and delivery of aviation synthetic fuel; (7) distribution methods available from the production facility; (8) whether delivery can be made on a free on board (FOB) destination basis (preferred method) or FOB origin basis; (9) financial ability to justify potential award of a supply-type contract; (10) estimated start-up cost to begin production of aviation synthetic fuel (specify scale of production); (11) estimated cost, variable and fixed, of producing a gallon of fuel; and (12) understanding of federal, state, and local environmental laws and regulations, and familiarity and experience with environmental compliance procedures and regulations for applicable states and U.S. Environmental Protection Agency (EPA) regions. In addition, interested parties should provide comments on the nature and level of federal and state incentives and/or obligations (e.g., R&D, capital investment, investment or production incentives) needed to develop and sustain long-term domestic commitments to producing aviation synthetic fuels.

As of this writing DESC has received an overwhelming response to its RFI from the industry. This would appear to augur well for the production of alternative fuels by the industry, because DoD is the single largest buyer of jet fuel in the country. Also, military logistics and national security should take precedence, and it remains to be seen just how the use of synthetic fuels will affect the fuel interchangeability, airframe compatibility, fuel efficiency, and engine operability of re-engined aircraft. Specifically, the FT fuel must be fully interchangeable with JP-8 fuel, and switching from one to the other must not cause any adverse effects.

In April 2006, under the provision of the Energy Policy Act of 2005 (P.L. 109-58), the Senate Energy Committee discussed the creation of technology for coal-to-liquid (CTL) fuel. The effort would comprise loan guarantees for building CTL plants producing over 10,000 bbl/day, up to $20 million in matching loan guarantees for large-scale CTL plants, and investment tax credits and expensing capped at $200 million. Thus, DOE has comprehensive plans to create a domestic CTL infrastructure.

SYNTHETIC FUEL PROPERTIES, SPECIFICATIONS, AND RE-ENGINING

Fuels for the military may not be sold into the commercial sector unless they meet certain specifications that are usually developed by a consortium of industry experts. For example, in the United States, the American Society of Testing and Materials (ASTM) International Committee D2 is in charge of development and modifications of ASTM D 1655, which contains the specifications for the commercial jet fuels Jet A and Jet A-1. Military standards are "owned" by the relevant organization, for example, the Air Force Petroleum Office is responsible for MIL-DTL-83133E, which specifies the properties of fuels to be purchased as JP-8 and JP-8+100. These specifications typically require that fuels be derived from petroleum distillate products. Thus, the commercialization of synthetic fuels produced from coal or other carbon sources such as natural gas or biomass via the FT process or any other process will not be possible until these standards are modified to allow the use of synthetic fuels produced by the military. Fortunately, much has been done in recent years to pave the way for synthetic fuels. The British Defense Standard DEF-STAN 91-91 was recently modified to allow the commercial use of 50:50 mixtures of synthetic fuels produced from coal and petroleum-derived jet fuels produced by Sasol Ltd. (South Africa). An effort is under way to permit use of fully synthetic jet fuel produced by that company. In addition, DoD, led by the Air Force Research Laboratory (AFRL), is in the process of formulating a standard to allow the use of synthetic fuels in military aircraft. The fuel properties of interest are these:

- API gravity and conductivity,
- Chemical composition,
- Thermal stability,
- Low-temperature properties (freeze point and viscosity),
- Elastomer swell,
- Fuel lubricity, and
- Combustion properties.

Recently, Harrison and Zabarnick (2006) reported on preliminary studies of the measured properties and behavior of synthetic FT-based jet fuels and compared them with conventional JP-8 fuel. Below is a brief description of their results.

- *Gravity and conductivity.* Fuel density affects the aircraft range and hence the flight mission capability. The FT fuel sample was 5 percent less dense than JP-8 fuel owing to the absence of high-density (~0.87 g/mL) aromatic compounds that are present in conventional petroleum fuels. Thus, blending the FT fuel with aromatic compounds will increase its density. For volume-limited aircraft, FT fuels may slightly decrease range, although some of the impact is offset by the higher gravimetric heating value of FT fuels. For weight-limited aircraft, some small benefits may be gained. In the aggregate, there is no adverse or beneficial effect on airplane configuration or fuel efficiency. If the standard JP-8 additive package (static dissipater, icing inhibitor, and corrosion inhibitor) is used, the FT fuel passes the specification test for conductivity.
- *Chemical composition.* Using ASTM D2425-93, Hydrocarbon Analysis Using Mass Spectrometer, it was found that typical JP-8 fuel samples contained approximately 60 percent paraffins, 20 percent cycloparaffins, and 20 percent aromatics. In contrast, the FT fuel samples contain mostly the same n- and isoparaffins as JP-8 but less than 1 percent cycloparaffins and aromatics. During combustion, the absence of aromatic compounds reduces the formation of polycyclic aromatic hydrocarbon (PAH) soot precursors. Also, synthetic FT fuels contain undetectable levels of heteroatomic polar species such as phenols (<15 mg/L) as compared with 100-600 mg/L in petroleum-derived fuels. This fuel property provides FT fuels with a high level of thermal stability.
- *Thermal stability.* This property refers to the ability of a fuel to resist formation of surface and bulk deposits upon exposure to elevated temperatures. High-thermal-stability fuels can be used as effective heat sinks for the thermal management of aircraft and engine components. Tests conducted at 140°C for 15 hr (oxidative stability) showed that petroleum-derived fuel deposited ~2 to 8 $\mu g/cm^2$; in contrast, synthetic FT fuels deposited ~1.5 $\mu g/cm^2$.
- *Low-temperature properties.* During high-altitude, long-duration (i.e., loitering) flight, jet fuel in the tank can approach very low ambient temperatures (<40°C). Thus, flowability, freeze point, and viscosity (for atomization) become important properties. The freeze point of synthetic

FT fuel was found to be as low as –59°C, well below the JP-8 specification of ≤–47°C. The FT fuel samples displayed a more gradual rise in dynamic viscosity than the petroleum-derived fuels, whose viscosity rose sharply. Also, the kinematic viscosity of FT fuels, although slightly higher than that of JP-8 fuel, was still well below the specification maximum viscosity, for JP-8, of 8 centistokes (cSt) at –20°C and, for Jet Propulsion Thermally Stable (JPTS), 12 cSt at –40°C.

- *Elastomer swell.* Most aircraft fuel system seals swell when exposed to fuel, especially to the aromatic and polar species (such as phenols and glycol-based fuel system icing inhibitors) present in petroleum-derived fuels. Graham et al. (2006) found that nitrile O-rings soaked in FT fuels showed very little swelling (<2 percent), whereas those soaked in JP-8 fuel swelled by approximately 16 percent. Thus, the nitrile swell characteristics of FT fuel can be improved by additives that increase swell, blending with petroleum-derived fuels, or the addition of aromatic species to prevent fuel system leaks.
- *Fuel lubricity.* Lubricity permits trouble-free operation of fuel delivery system components such as fuel pumps and flow-control valves. The JP-8 fuel specification calls for the addition of a corrosion inhibitor, which also improves fuel lubricity. Tests based on ASTM D 5001, Ball-on-Cylinder Lubricity Evaluator (BOCLE), showed wear scars with FT fuels over the range 0.82 to 0.88 mm as compared with a maximum wear scar of 0.85 mm for Jet A-1 fuel. Clearly, FT fuels exhibit borderline lubricity, and corrosion inhibitor/lubricity improver additives are required to improve fuel lubricity.
- *Combustion properties.* Emissions of soot and NO_x from combustion are important properties. Although DoD aircraft are exempt from some EPA regulations, there are potential conflicts with European Union rules, which might limit tanker deployment. Evaluations of soot emissions from FT fuels, FT/JP-8 blends, and JP-8 were performed using a T63-A-7000 turboshaft engine. Results showed reduced particulate emissions for both idle and cruise conditions. The reduction was attributed to reduced aromatic concentration, which reduces PAH (soot nuclei precursors) formation during combustion. Finally, no changes in NO_x emissions were observed.

Finding 7-1. Alternative fuels have properties that have substantial advantages over conventional fuels in areas of thermal stability, low-temperature operability, and soot emissions. However, two properties—elastomer swell and lubricity—may need to be modified. Detailed data on fuel properties are lacking.

Recommendation 7-1. The committee recommends that the Air Force Office of Scientific Research and/or the AFRL should initiate a comprehensive program of fundamental research covering FY08 to FY15 with an annual budget of $5 million. The goal of this program should be to study properties of surrogate fuels, synthetic fuel CTL process technologies, synthetic fuels produced from a variety of feedstocks (such as coal, oil shale, and biomass), and synthetic–conventional fuel blends. Systematic molecular and chemical kinetics modeling studies should be performed to establish a fundamental database of fuel and combustion properties. This level of funding is urgently required to develop cooperative research programs (such as the Multidisciplinary University Research Initiative) throughout the nation.

CHALLENGES TO PRODUCING DOMESTIC ALTERNATIVE FUELS

Congress has requested a development plan from DOE to facilitate the production of liquid fuels from coal (P.L. 109-163, Section 1090). It is estimated that domestic energy sources (coal, shale, renewables, and alternative sources) have more than three times as much potential as estimated Middle East reserves. These fuels have not come into widespread commercial use in the United States, partly because of their cost; however, with rising petroleum cost and increased production volume, some alternative fuels are beginning to look competitive, and technology is improving. The fact that Sasol in South Africa, with FT fuel, and others in Canada, with tar sands, are in production is promising.

Now, the challenge is to develop these domestic resources in partnership with other government agencies and private industry. Economic barriers include uncertainties surrounding the price of oil, high capital and operating costs, and investment risks. Environmental barriers include the carbon dioxide (CO_2) produced during the preparation of synthesis gas for the FT process and the expansion of coal refining, processing, and production. Barriers to commercial deployment include competition for process equipment, the scarcity of engineering skills, and the transportation of feedstock to the processing location.

Finding 7-2. As shown in Figure 7-1, industry needs DoD leadership to bridge the Valley of Death and to obtain secure domestic sources of fuel. In October 2005, DoD established the Energy Senior Focus Group, whose chair is the Secretary of the Air Force (SAF/US), and has since published OSD guidance on energy policy. An Air Force energy document (Sega, 2006) describes the near- and mid-term acquisition and technology strategy as follows:

- Alternative Fuels Initiative (coal, natural gas, oil shale, and biomass),
- Aircraft Technology Initiative (VAATE engines and ultralightweight aircraft structures), and
- Modernization Initiative (re-engining studies for improved air vehicle efficiency).

Recommendation 7-2. The Alternative Fuels Initiative should have as its primary goal the creation of a domestic synthetic fuels industry.

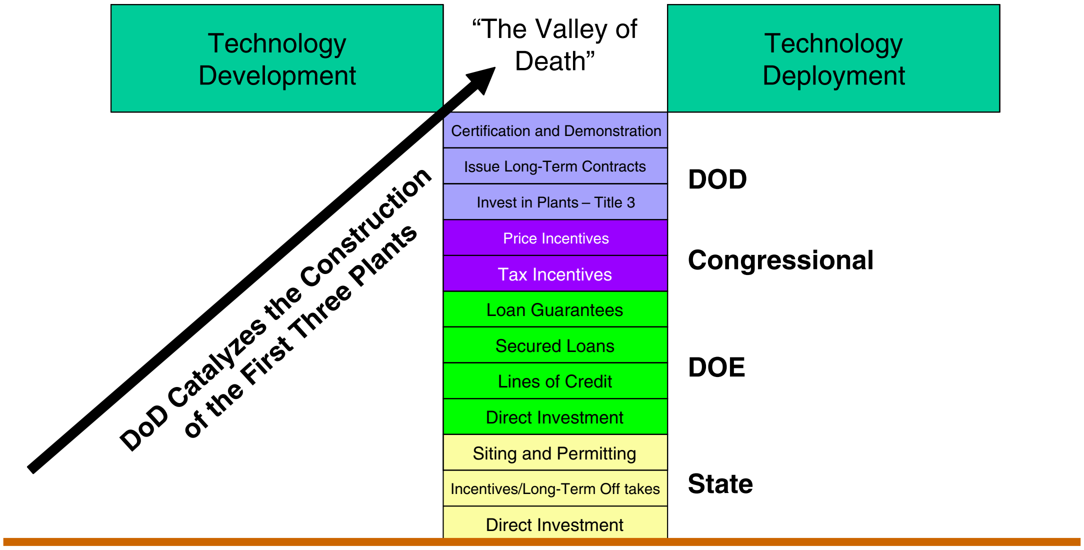

FIGURE 7-1 DoD leadership required to bridge the Valley of Death. SOURCE: Harrison (2006).

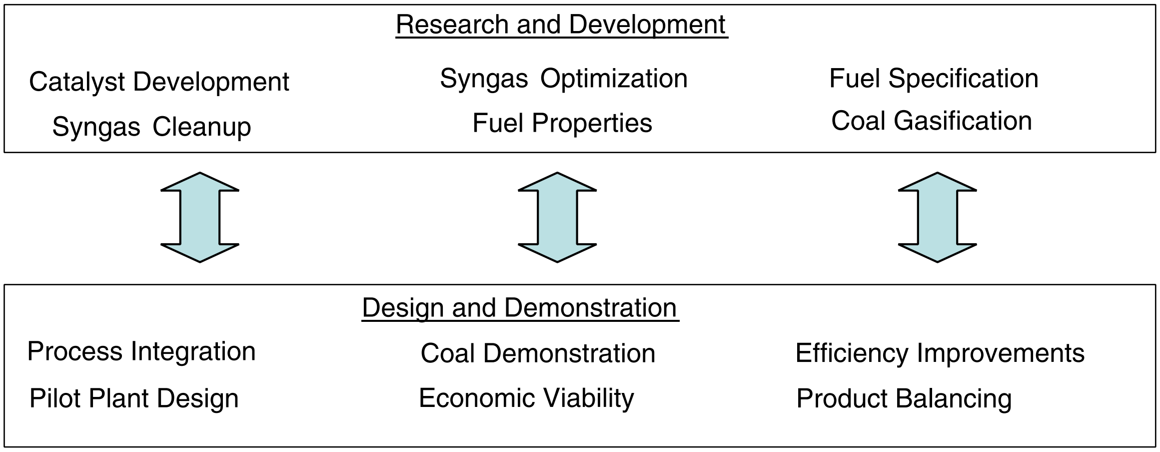

FIGURE 7-2 Suggested two-tiered approach for developing a domestic synthetic fuels industry. SOURCE: Personal communication from Steven Zabarnick, Distinguished Research Chemist, University of Dayton Research Institute, to committee member Dilip Ballal on September 1, 2006.

This goal should be pursued by two parallel pathways, as shown in Figure 7-2: (1) creation of subscale facilities to confirm the viability of the synthetic fuels processes and procedures, as well as to build an experience base in their operation, and (2) a simultaneous R&D effort directed at improving efficiency, economic viability, and product properties in these subscale facilities.[1] It is essential to both build the subscale facilities and perform the R&D work to establish the knowledge base and optimize the operating variables for the creation of full-scale plants. The results of the R&D work will be closely applied to operating facilities to ensure that these efforts are both useful and relevant.

> **Finding 7-3.** The Alternative Fuels Initiative has already called for procuring 100,000 gallons of natural gas FT synthetic fuel in FY06 to conduct B-52 flight demonstration tests and to finalize cost/benefit modeling with DOE. As the fuel is certified for military aviation use and logistics and handling experience is gained, more fuel will be needed. Thus, in June 2006, DESC issued an RFI to seek industry proposals to supply 200 million gallons of alternative fuel from domestic sources to reduce foreign oil dependence and greenhouse gas emissions.

> **Recommendation 7-3.** DoD, through the AFRL, should commit to building an assured aerospace fuels research facility (AAFRF) that would perform R&D essential to the development of CTL synthetic fuel technology. Such a facility could comprise a modular research-scale pilot facility to test different catalysts, coal contaminants (mercury and sulfur), syngas cleanup, syngas and CTL fuel yield optimization, control over the quality of jet fuels, fuels test equipment, and combustion burners for emissions testing. This effort should be funded at $7 million/yr over FY08-FY15. The AAFRF will be a national resource: It will test fuels procured by DESC and build a database of fuel

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[1] Personal communication from Steven Zabarnick, Distinguished Research Chemist, University of Dayton Research Institute, to committee member Dilip Ballal on September 1, 2006.

properties and fuel specifications for certification. It will also serve as a research tool for professional researchers from government, academia, and industry as well as a training ground for skilled operators, technicians, and researchers for future commercial facilities.

Finding 7-4. Synthetic fuels and the creation of an industry to make and distribute them offer numerous advantages. Synthetic fuels produced via the FT process are inherently clean. The fuel produced contains significantly less sulfur (<1 ppm) than any other proposed low-sulfur fuels, such as ultra-low-sulfur diesel (<15 ppm) and low-sulfur diesel (<50 ppm). Thus, FT fuels could potentially be used directly as high-value diesel while producing no environmentally detrimental sulfur oxides and less particulates upon combustion (Norton et al., 1998). In addition, FT fuels have the important advantage of being fungible with the current transport/pipeline infrastructure. Creation of a synthetic fuels industry will create a significant number of jobs in many areas, including mining, engineering, and transportation.

DoD is currently studying a jet fuel specification that would allow the use of synthetic fuels produced by the FT process. Sasol Ltd. of South Africa has produced synthetic aviation fuel for commercial use for many years, demonstrating a viable market in the public sector. Fuel produced via the FT process could be used directly as a diesel fuel or upgraded using extant processing techniques to form gasoline; both uses promise growing markets. Synthetic fuel feedstocks include coal, oil shale, and biomass.

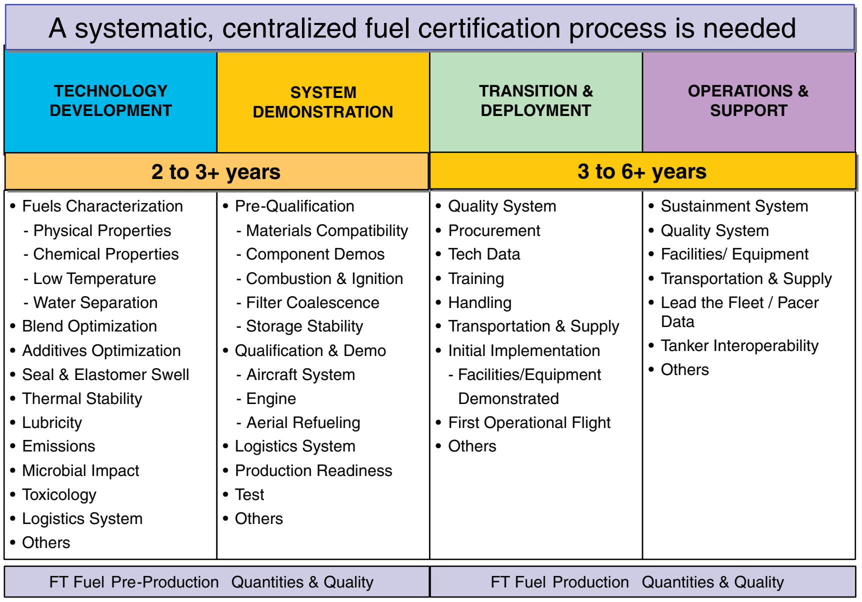
Recommendation 7-4. DoD should take steps beyond the B-52 flight demonstration to reaffirm its long-term commitment to synthetic fuels for its fleet of aircraft. This includes qualifying an FT fuel specification and fully certifying aircraft re-engined with, for example, CFM56 and large tanker platforms such as the KC-135R/T, C-130, and KC-10.

Finding 7-5. A number of government incentives are either in place or have been proposed to encourage development of a domestic CTL industry. Rep. John Shimkus (R-Ill.) introduced a House bill in May 2006 to extend a $0.50 per gallon tax credit originally slated for ethanol and biodiesel fuels to alternative fuels produced from coal. The bill would also extend the deadline for these credits from 2009 to 2020. The Energy Policy Act of 2005 contains investment tax credits for advanced coal and industrial gasification projects. Recent government initiatives could raise the current industrial gasification investment tax credit from the current $350 million to $850 million.

Recommendation 7-5. DoD, as the single largest buyer of jet fuels in the nation, should consider other incentives such as floor price guarantees for jet fuels produced to assure an acceptable rate of return, loan guarantees to allow private financing under reasonable terms, additional tax incentives such as investment tax credits, fuel excise tax exemptions, and/or accelerated depreciation.

STRATEGY FOR QUALIFYING ALTERNATIVE FUELS

Finding 7-6. A systematic, centralized fuel certification process is needed. This includes not only R&D but also fuel blending, handling, storage, and transportation issues. Also, over the years the number of conventional fuels on the battlefield has swollen from about 6 (in the 1990s) to 10 (today), and this number is expected to grow to over 12 by 2010. The unique properties of synthetic fuels promise to turn the idea of a single fuel for the battlefield into a reality, greatly simplifying battlefield



A systematic, centralized fuel certification process is needed

TECHNOLOGY DEVELOPMENT	SYSTEM DEMONSTRATION	TRANSITION & DEPLOYMENT	OPERATIONS & SUPPORT
2 to 3+ years		3 to 6+ years	
• Fuels Characterization - Physical Properties - Chemical Properties - Low Temperature - Water Separation • Blend Optimization • Additives Optimization • Seal & Elastomer Swell • Thermal Stability • Lubricity • Emissions • Microbial Impact • Toxicology • Logistics System • Others	• Pre-Qualification - Materials Compatibility - Component Demos - Combustion & Ignition - Filter Coalescence - Storage Stability • Qualification & Demo - Aircraft System - Engine - Aerial Refueling • Logistics System • Production Readiness • Test • Others	• Quality System • Procurement • Tech Data • Training • Handling • Transportation & Supply • Initial Implementation - Facilities/Equipment Demonstrated • First Operational Flight • Others	• Sustainment System • Quality System • Facilities/ Equipment • Transportation & Supply • Lead the Fleet / Pacer Data • Tanker Interoperability • Others
FT Fuel Pre-Production Quantities & Quality		FT Fuel Production Quantities & Quality	

FIGURE 7-3 Candidate synthetic fuels qualification strategy. SOURCE: Harrison (2006).

logistics. Their low emissions and high thermal stability makes them ideal for replacing JP-8 and Jet A-1 in aircraft, high cetane number (>74) allows their use in army and marine ground vehicles, and the absence of sulfur and aromatics could enable their use as hydrocarbon reformers for fuel cell power generation. These domestically produced fuels represent a quantum leap in simplifying logistics and decreasing our dependence on foreign oil.

Recommendation 7-6. DoD should, over the period FY08-FY15, put into place a comprehensive program of candidate fuel qualification strategy comprising four phases: R&D, system demonstration, transition and deployment, and operations and support (see Figure 7-3). This work should be funded at $15 million per year.

COAL-TO-LIQUID FUEL TECHNOLOGY PROMOTION ACT

In May 2006, Senators Bunning, R-Ky., and Obama, D-Ill., introduced S.3325, Coal-to-Liquid Fuel Promotion Act of 2006. If passed, this legislation will help create the infrastructure needed to make CTL a viable domestic energy source.[2] In the CTL process, coal is gasified, the gas is run through the FT process, and the resulting fuel is refined into an environment-friendly diesel fuel that has no sulfur or nitrogen. With a heavy investment in CTL, the United States will wean itself from foreign sources of energy and at the same time create jobs. The CTL legislation has three parts: (1) loan guarantees for construction and planning of CTL plants, (2) expansion of current investment tax credits and expensing

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[2] As of January 23, 2007, S.3325 has not been enacted into law. More information can be found at http://thomas.loc.gov/cgi-bin/bdquery/z?d109:s.03325:. Last accessed on January 23, 2007.

provisions and extension of the fuel excise tax credit (from 2009 to 2020), and (3) funding for DoD to purchase, test, and integrate these fuels into the Strategic Petroleum Reserve (SPR) for national security and defense. Specifically, it authorizes the construction of SPR storage facilities for CTL fuel away from states bordering the Gulf of Mexico.

> **Finding 7-7.** The CTL Fuel Promotion Act of 2006 authorizes DoD to hold up to 20 percent of the SPR in the form of CTL finished fuels. It also gives DoD multiyear contracting authority for up to 25 years and authorizes funding for the Air Force CTL R&D and testing program.

SUMMARY

This chapter addresses fuel properties and specifications and their impact on re-engining; challenges for the domestic production of alternative fuels; and a strategy for qualifying alternative fuels. Many properties of alternative fuels have substantial advantages over conventional fuels, and the unique properties of synthetic fuels may bring DoD closer to the single battlefield fuel concept, greatly simplifying the logistics of battle. Detailed data on fuel properties and fundamental knowledge of fuel combustion are lacking. Domestic energy sources (coal, shale, renewables, and alternative sources) have more than three times as much potential as estimated Middle East reserves. The challenge remains to develop these resources in partnership with other government agencies and private industry. Economic barriers, environmental barriers, and barriers to commercial deployment must be overcome, and the industry needs DoD leadership to bridge the gap between technology development and deployment. A systematic, centralized fuel certification process is needed. This includes not only R&D but also fuel blending, handling, storage, and transportation issues. The unique properties of synthetic fuels allow their use by all the services. These domestically produced fuels represent a quantum leap in simplifying logistics and decreasing our nation's dependence on foreign oil.

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8

Technology Preparedness and Insertion

INTRODUCTION

Some benefits of re-engining programs are due to the fact that newer engine models typically embody more advanced technologies and design and manufacturing processes than were available for the original engine. These new technologies provide improvements in aerothermodynamics, structures, materials, and controls and result in an engine that is more powerful and lighter in specific weight, consumes less fuel, and is more durable, reliable, and maintainable than the engine being replaced. For large nonfighter aircraft for military applications, engine usage (flight hours per year) is low enough that several generations of technology may evolve during the lifespan of any given engine. The performance, fuel consumption, and support cost differences between a baseline engine and a re-engining candidate may therefore be very large.

Although the benefits of re-engining with newer technology engines are clear, the costs associated with procurement and the nonrecurring development cost required to integrate the new engine can be prohibitively high. There is a clear trend away from new centerline engines and toward longer service life for fielded, on-wing engines, so classic re-engining opportunities will become rarer. It is thus important for national turbine engine science and technology (S&T) efforts to recognize this trend and place greater emphasis on the continual transition of new technology to fielded engines, in particular, technology that can reduce fuel consumption. The former Engine Model Derivative Program (EMDP) is a noteworthy example of successful technology transition from research and development programs to fielded engines.[1]

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[1] An EMDP was created in 1978 to develop an alternative engine to the F100. The Air Force was concerned about early operational and supportability problems with the F100 engine fleet and wanted to make the F-16 engine purchase competitive to obtain cost and support savings (Irwin, 2006).

TURBINE ENGINE SCIENCE AND TECHNOLOGY OVERVIEW

Until 2005, U.S. turbine engine research was guided by the Integrated High Performance Turbine Engine Technology (IHPTET) program. IHPTET was initiated in 1987 with very aggressive technical goals, essentially achieving a 100 percent improvement in turbine engine capability based on a 1987 state-of-the-art baseline engine by the turn of the century. IHPTET featured specific goals in each of three engine classes—namely, turbofan/turbojet, turboprop/turboshaft, and expendable engines. For the turbofan class, the primary goal of IHPTET was to double the engine thrust to weight ratio (T/W). Although IHPTET made significant progress toward its goals, the program focused on low-bypass-ratio, fighter/attack-class engines, and payoffs for large-bypass-ratio, transport-class engines occurred primarily as a spin-off from the fighter/attack application. Thrust-specific fuel consumption (TSFC) was regarded as important, but not as critical as T/W.

With the conclusion of IHPTET in 2005, the Versatile Affordable Advanced Turbine Engines (VAATE) program became the nation's premier turbine engine S&T program.[2] VAATE has been structured to take advantage of the features that made IHPTET successful. These include coordination between DoD, NASA, academia, and industry, with the Federal Aviation Administration (FAA) and DOE joining the effort as well. The breadth of this integrated team allows the VAATE program to coordinate gas turbine technology development strategy at the national level while leveraging funding of the constituent organizations. A fundamental goal of VAATE is to advance overall air system capability with a capability-focused investment strategy. The scope of VAATE is thus significantly greater than the rotating machinery focus of IHPTET and will encompass the entire propulsion/power system, including inlet/nozzle integration, thermal and power management, integrated controls, and prognostics and health management. This approach requires optimization of integrated propulsion capability at the aircraft system level, rather than optimization of just the engine turbomachinery. To this end, the major aircraft manufacturers are full partners on the VAATE industry team.

The VAATE program goal is to realize a 10-fold improvement in the affordable capability of a turbine-engine-based propulsion system. Here, "affordable capability" is defined as the ratio of propulsion system capability to cost. Capability in this context measures technical performance parameters, including thrust, weight, and fuel consumption. Cost is the total cost of ownership and includes development, procurement, and life-cycle maintenance cost (excluding fuel). These improvements are to be realized relative to a baseline representative of year 2000 state-of-the-art systems.

Specific measurable technical improvements, such as thrust, weight, TSFC, and life-cycle cost, are called "goal factors" in the VAATE lexicon. The overall VAATE goal, expressed as a capability-to-cost index (CCI), is defined by the following function of the goal factors, where each factor is expressed as a ratio between the subject and a contractor-chosen reference system:

$$\mathrm{CCI} = \left(\frac{{}^{\mathrm{T}}\!/_{\mathrm{W}}}{\mathrm{TSFC}} \right) \times \frac{1}{\mathrm{cost}}$$

While each VAATE contractor is free to determine the specific combination of goal factors and product application that comprise its offering to achieve the CCI goal, it is important to note that the fundamental physics-based turbine engine technology barriers, such as temperature, pressure ratio, and

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[2] For additional information on the VAATE program, please see the American Institute of Aeronautics and Astronautics (AIAA) VAATE position paper at http://pdf.aiaa.org//downloads/publicpolicypositionpapers//VAATE.pdf. Last accessed on September 11, 2006.

materials, are the same regardless of the exact architecture, configuration, and application of the engine. Without guidance, VAATE contractors may choose to emphasize performance (T/W) improvement for clean-sheet, high Mach or fighter/attack-class engines rather than specific fuel consumption (SFC) and cost improvements for the subsonic, high-bypass-ratio engines necessary for large nonfighter aircraft. Several technologies that are of specific interest to this class of application are shown in Figure 8-1. Other advanced technologies, such as unducted or geared high-bypass-ratio fans and low-pressure spool power extraction, have been shown to yield fuel efficiency improvements and might be amenable to eventual re-engining applications. Environmental constraints, such as noise and emissions levels, are additional considerations for the technology planning process.

Finding 8-1. Engine fuel efficiency was an important consideration but not a primary focus of previous S&T programs such as IHPTET. VAATE allows greater leeway for emphasis on fuel efficiency, but it is not clear that such focus will materialize without specific DoD direction.

Recommendation 8-1. The Air Force should review and amend the VAATE plan and its engine development programs, as appropriate, to provide an explicit emphasis on technology to improve fuel efficiency and reduce operational costs, to transition those improvements to fielded, high-bypass-ratio engines, and to consider research aimed at the reduction of particulate, hydrocarbon, sulfur, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and noise emissions by the DoD systems.

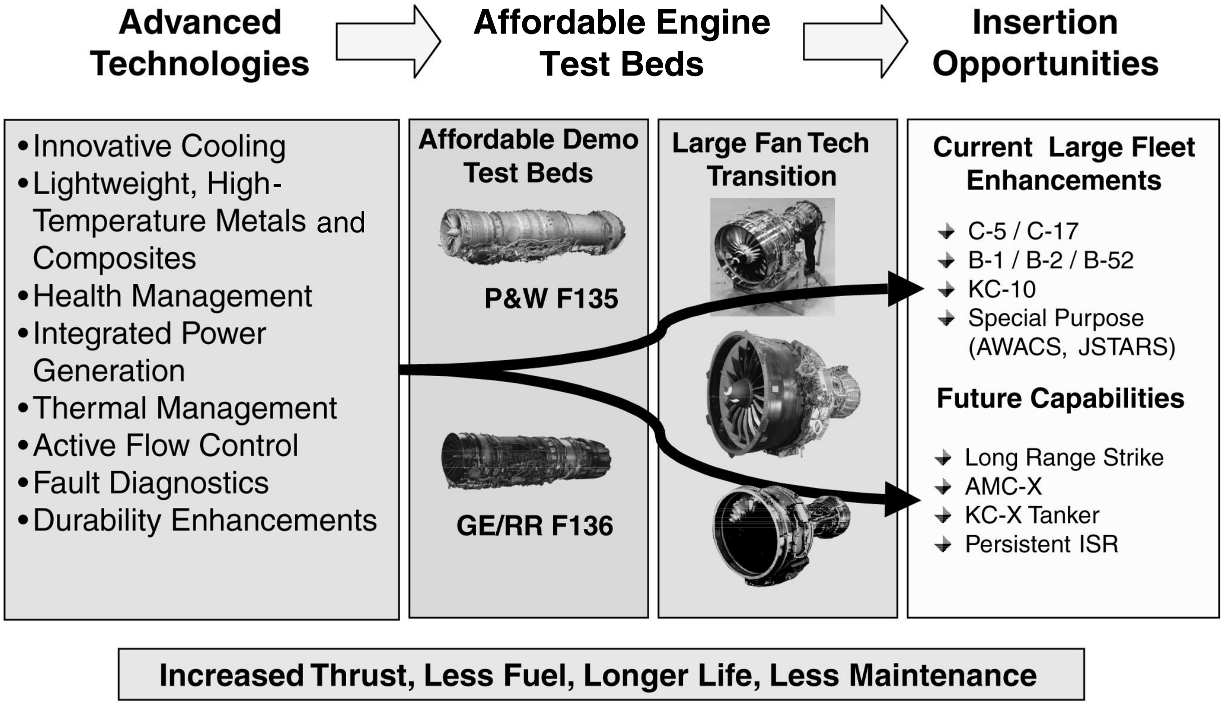


FIGURE 8-1 Key advanced technologies for large turbofan engines that will be developed through the VAATE program. ISR, intelligence, surveillance, reconnaissance. SOURCE: Personal communication from Timothy Lewis, Air Force Research Laboratory, to committee member Jeffrey Hamstra on August 24, 2006.

POTENTIAL FOR SPECIFIC FUEL CONSUMPTION IMPROVEMENT

Outside the gas turbine engine community, many believe that turbine engine performance and efficiency have reached a natural limit. In fact, just the opposite is true: There remains substantial potential for improving the current state of the art and more nearly attaining theoretical limits. The ideal cycle based on optimum stoichiometric combustion properties is a sign of how far the gas turbine engine remains from its theoretical limits in terms of the key fuel efficiency metric.

Turbine engine fuel efficiency has improved dramatically from the 1940s to today. Each new technology improvement, whether in component aerodynamics, materials, or turbine cooling, has allowed increments to overall pressure ratio and turbine inlet temperature, resulting in improved fuel efficiency across a diverse range of engine applications. As shown in Figure 8-2, current state-of-the art engine technology reaches only approximately 38 percent of the stoichiometric limit of gas turbine engines. Through a combination of technologies offered by the VAATE program, a 25 percent improvement in fuel efficiency is anticipated, a substantial improvement over today's state of the art.

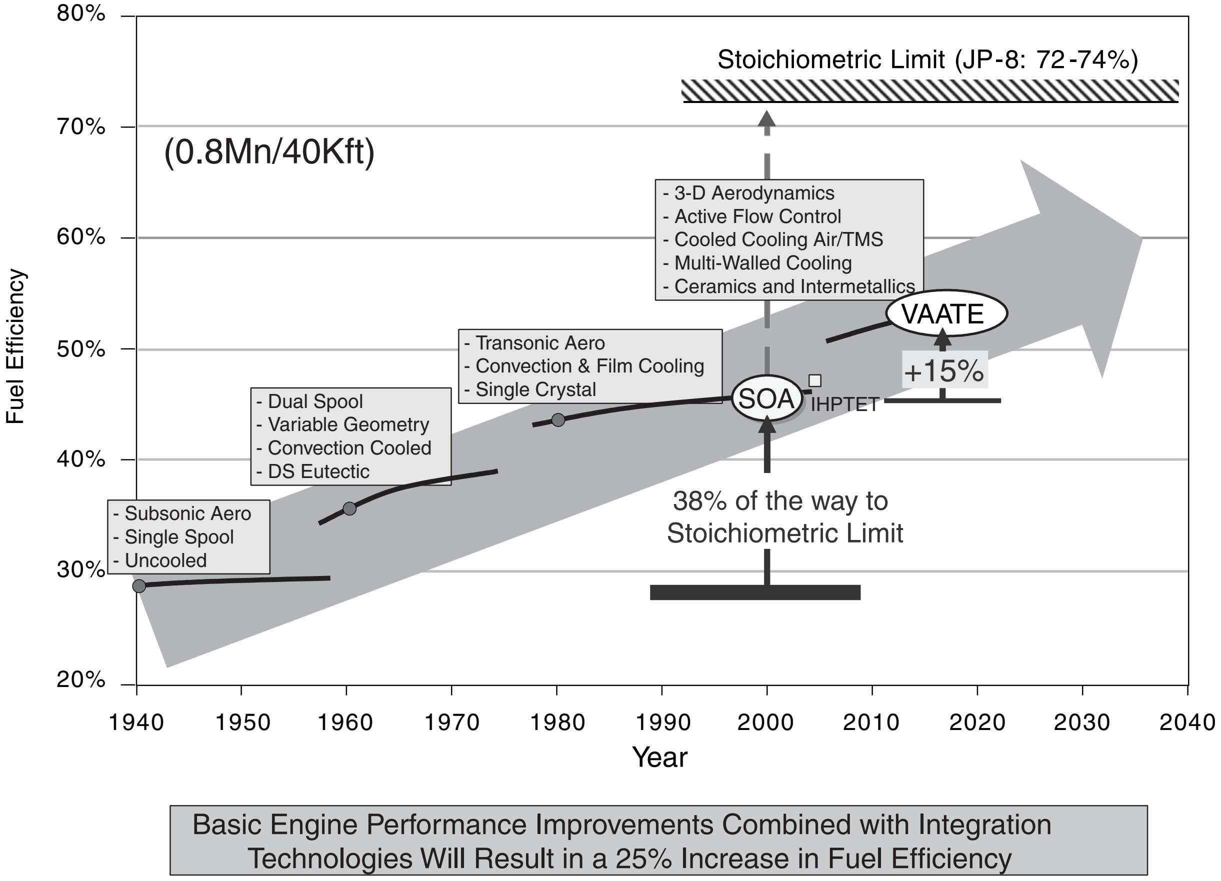


FIGURE 8-2 Progress in gas turbine thermodynamic cycle fuel efficiency. SOURCE: Harrison (2006).

Finding 8-2a. Current state-of-the-art engine technology has closed only 38 percent of the fuel efficiency (i.e., TSFC) gap between 1940s-vintage jet engines and theoretical limits.

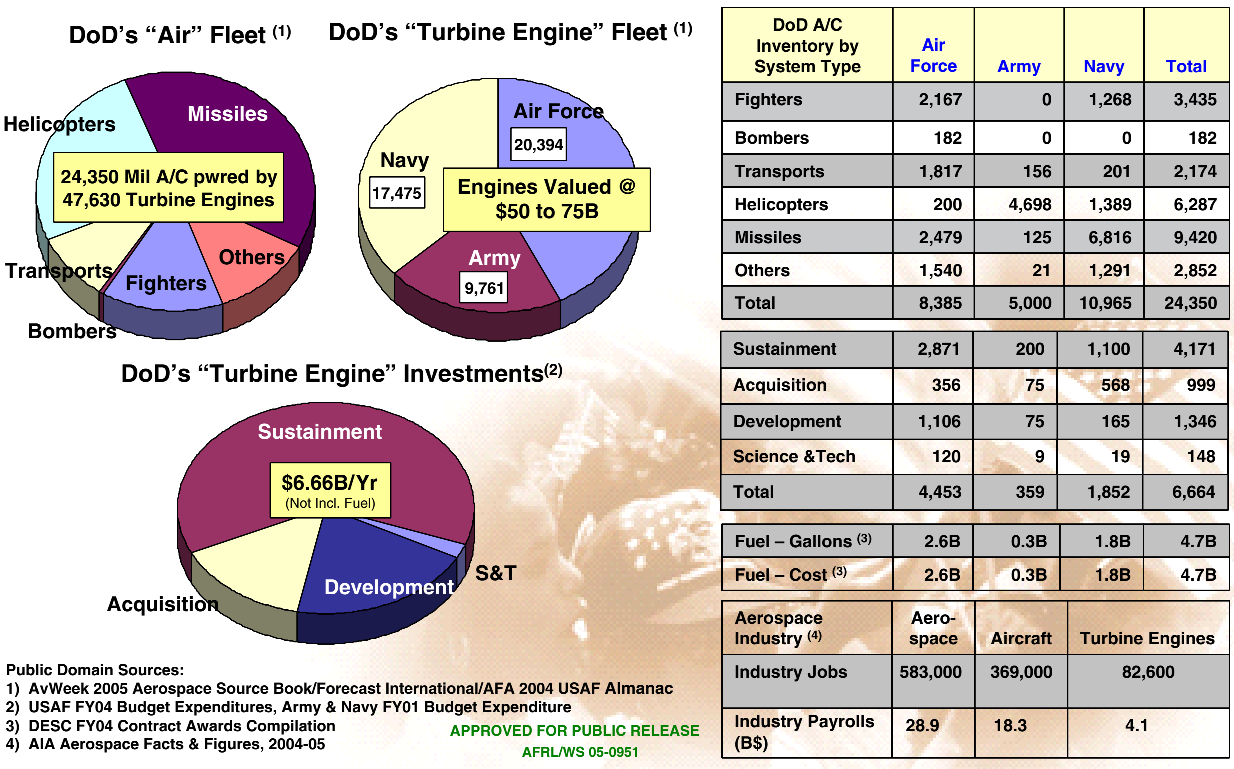
Finding 8-2b. Through a combination of technologies offered by further development, an additional 25 percent improvement in turbine engine fuel efficiency is anticipated.

Recommendation 8-2. As an additional facet of VAATE, the Air Force Research Laboratory (AFRL) should establish a technology insertion plan for SFC improvements integrated across the top fuel-consuming DoD systems.

COMPONENT IMPROVEMENT AND ENGINE MODEL DERIVATIVE PROGRAMS

This section discusses the issues and opportunities associated with a large and growing portion of the DoD aircraft propulsion systems. Figure 8-3 shows that approximately $4.2 billion per year of the total $6.6 billion DoD yearly gas turbine engine budget is spent on the sustainment of existing engines (AFRL, 2005).

The cost of fuel burned by the existing fleet is currently estimated at $11.75 billion annually based on a fuel cost of $2.50 per gallon (Connelly, 2006; Harrison, 2006). The projected weapon system force structure for the next 15 to 20 years indicates that currently fielded systems will continue to dominate



DoD A/C Inventory by System Type	Air Force	Army	Navy	Total
Fighters	2,167	0	1,268	3,435
Bombers	182	0	0	182
Transports	1,817	156	201	2,174
Helicopters	200	4,698	1,389	6,287
Missiles	2,479	125	6,816	9,420
Others	1,540	21	1,291	2,852
Total	8,385	5,000	10,965	24,350
Sustainment	2,871	200	1,100	4,171
Acquisition	356	75	568	999
Development	1,106	75	165	1,346
Science &Tech	120	9	19	148
Total	4,453	359	1,852	6,664
Fuel – Gallons (3)	2.6B	0.3B	1.8B	4.7B
Fuel – Cost (3)	2.6B	0.3B	1.8B	4.7B

Aerospace Industry (4)	Aero-space	Aircraft	Turbine Engines
Industry Jobs	583,000	369,000	82,600
Industry Payrolls (B$)	28.9	18.3	4.1

Public Domain Sources:
1) AvWeek 2005 Aerospace Source Book/Forecast International/AFA 2004 USAF Almanac
2) USAF FY04 Budget Expenditures, Army & Navy FY01 Budget Expenditure
3) DESC FY04 Contract Awards Compilation
4) AIA Aerospace Facts & Figures, 2004-05

FIGURE 8-3 DoD investment in turbine engines. A/C, aircraft. SOURCE: AFRL (2005).

and that new systems will be acquired at slower rates and in smaller numbers than the legacy fleets they replace. This will lead to an ever-increasing aging of the DoD gas turbine fleet. By 2020 most of the existing gas turbine engines will have reached or exceeded their design life and will need service life extensions. To address this reality, component improvement programs (CIPs) focus on several key areas, including decreasing Class A mishaps, increasing time on wing, decreasing fuel burn, and extending service life (Fecke, 2006). In many cases, new business models will be required to capture opportunities for incorporating new technologies or component improvements into the existing fleet to reduce the cost of sustainment and fuel for current engines. Current business practices, with different colors of money for CIPs, depot maintenance and support, and operational fuel cost, create artificial roadblocks to maximizing DoD's return on S&T investments. New business models, coupled with modest investments, could be leveraged for the existing fleet.

DoD aircraft systems are continually modernized in order to remain viable and responsive to the warfighter. These upgrades occur to address identified performance deficiencies or to grow existing systems to provide new mission capabilities. Figure 8-4 indicates that more capable aircraft typically weigh more, generate more drag, and have larger electrical/mechanical power loads, leading to increased demands on the aircraft propulsion system.

A proven cost-effective and efficient approach to increasing propulsion capability is the development of derivative versions of existing engines. Derivative engines are developed by transitioning newer technology into existing legacy propulsion systems, improving performance and power. Such engines have been used very successfully for both military and commercial applications since they offer significant cost, schedule, and risk advantages in comparison to new centerline engines. There is currently no active programmatic vehicle for increasing the performance of legacy propulsion systems by developing derivative engines. The EMDP, which was canceled in 1998, was just such an effective vehicle, and its cancellation resulted in two significant gaps in the DoD engine development process. The first gap is the inability to conduct timely studies of propulsion system enhancement or to develop technology transition roadmaps to support and complement aircraft modernization and capability growth studies prior to acquisition Milestone A. The second gap is the lack of a propulsion technology demonstration process to mature technology from Technology Readiness Level (TRL) 6 (demonstration in a relevant system) to TRL 7 (demonstration through initial flight test). This gap results in either increased risk or the inability to incorporate new technology into the propulsion system past acquisition Milestone B.

In the past, EMDPs were a very cost-effective method to improve capabilities and decrease the cost of sustainment. For example, the EMDP for the F100-PW229, developed for the F-15E, increased capabilities and decreased the cost of supportability (i.e., lowered the cost per flying hour by reducing both scheduled and unscheduled shop visits and reducing the rate of Class A mishaps). Similarly, the F101, F110, and F108 common core design, shown in Figure 8-5, has been a very cost-effective method using derivative engines to provide power for a wide range of aircraft.

Across DoD, a new capability-based assessment process has been implemented to define the requirements for upgrades to existing weapon systems or for an entirely new weapon system. After a capability gap or shortfall has been identified, determining how best to provide the desired capability begins with the weapon system studies. The initial capability document is developed bearing in mind the "art of the possible," based on available technologies. Possible solutions are assessed using a concept of operations (CONOPS)-based Analysis of Alternatives, and a concept is chosen for further refinement and potential technology development.

The capability assessment sets forth requirements for the weapon system. However, the propulsion system capability requirements are derived from the aero performance requirements of the weapon system and the subsystem functional interface requirements. The systems engineering process may not

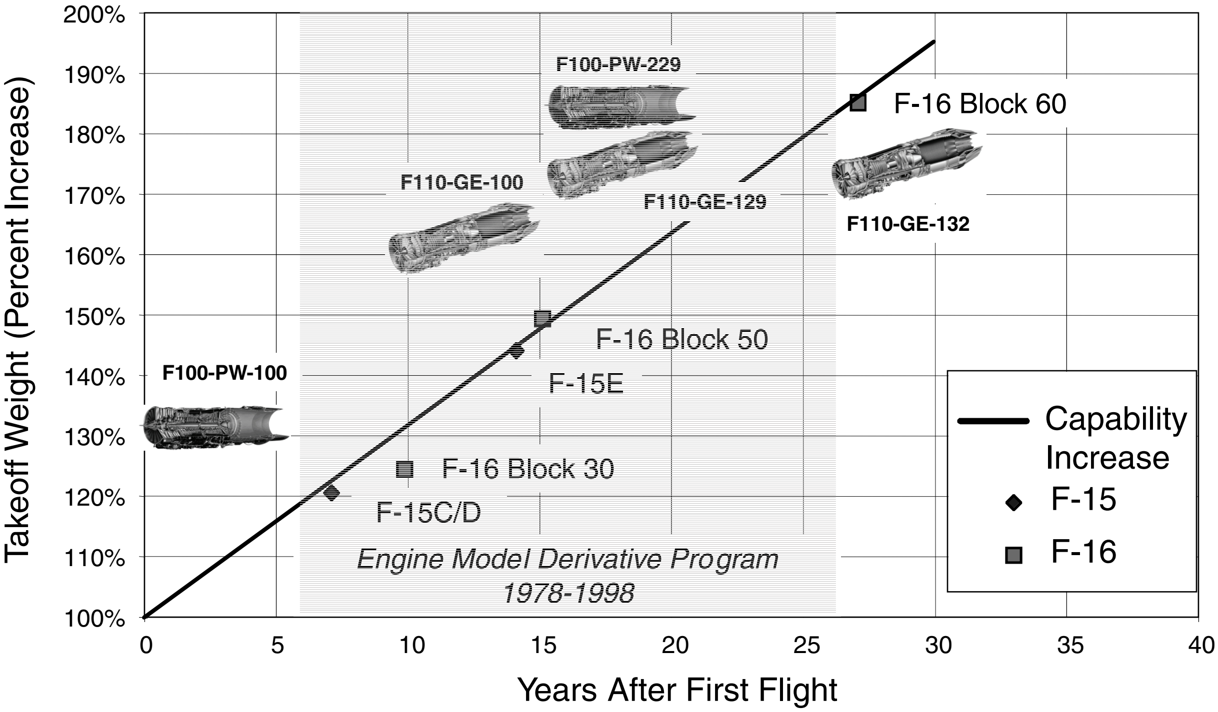


FIGURE 8-4 Engine model derivative program provides propulsion capability increases for F-15 and F-16 aircraft. SOURCE: Personal communication between Mark Amos, Agile Combat Support Wing, Wright-Patterson Air Force Base, and NRC staff member Carter Ford on July 7, 2006.

generate quantitative propulsion system requirements until the weapon system enters systems design and development. This delay, coupled with the lack of funding because the EMPD was dropped, is limiting the benefit that DoD could achieve from derivatives of existing engines.

> **Finding 8-3.** Unless strong action is taken, the growing proportion of the DoD propulsion budget needed for sustainment of the existing fleet and fuel for it will lead to a "death spiral" in which the share of budget available for technology development and transition will be continuously shrinking.

> **Recommendation 8-3.** The Air Force and DoD should improve synergy between DoD and commercial upgrade programs by improving the tracking of commercial upgrades and using the downtime during aircraft depot maintenance as an opportunity to upgrade engines to more commercial configurations, as appropriate.

> **Finding 8-4.** The CIP, like the EMDP before it, is highly effective in transitioning technology to fielded engines.

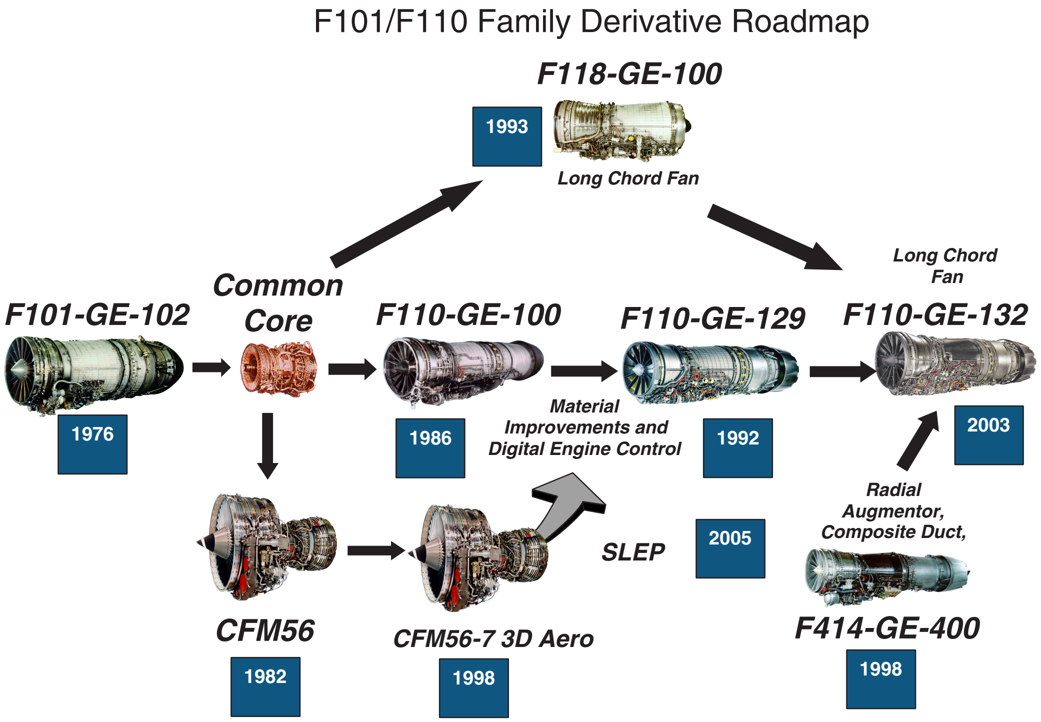


FIGURE 8-5 A common core approach can be used to propagate technology across a range of engine models. SLEP, service life extension program. SOURCE: GE Aircraft Engines.

> **Recommendation 8-4.** The Air Force and DoD should reinvigorate the CIP and the propulsion capability enhancement programs and combine the responsibility for component improvement, sustainment, and fuel burn under one budget authority to allow it to capture opportunities to reduce fuel burn and cost.

TURBINE ENGINE SCIENCE AND TECHNOLOGY FUNDING

Gas turbine engines will continue to be the predominant military propulsion source for the foreseeable future. To maintain air superiority, it is critical for the United States to maintain technological superiority in gas turbines. The technology developed in the IHPTET program, coupled with NASA turbine programs and the DoD Manufacturing Technology (ManTech) programs, is allowing the United States to field the most advanced gas turbines in the world (e.g., the F119, F135, and GE90 families of engines). With the overall reduction of the NASA and ManTech programs, VAATE must bear the burden of U.S. gas turbine engine S&T advancement.

Turbine engine S&T programs properly culminate with first demonstrations of the core technology and then proceed to full-engine laboratory demonstrations to mature the technology to TRL 6 and prove out transition capability. Previous generations (IHPTET program bases) of turbine technology development depended on these tests to be run at least once a year, and often twice, to meet timely and necessary technology transition goals to new and fielded military and commercial engines. However, as

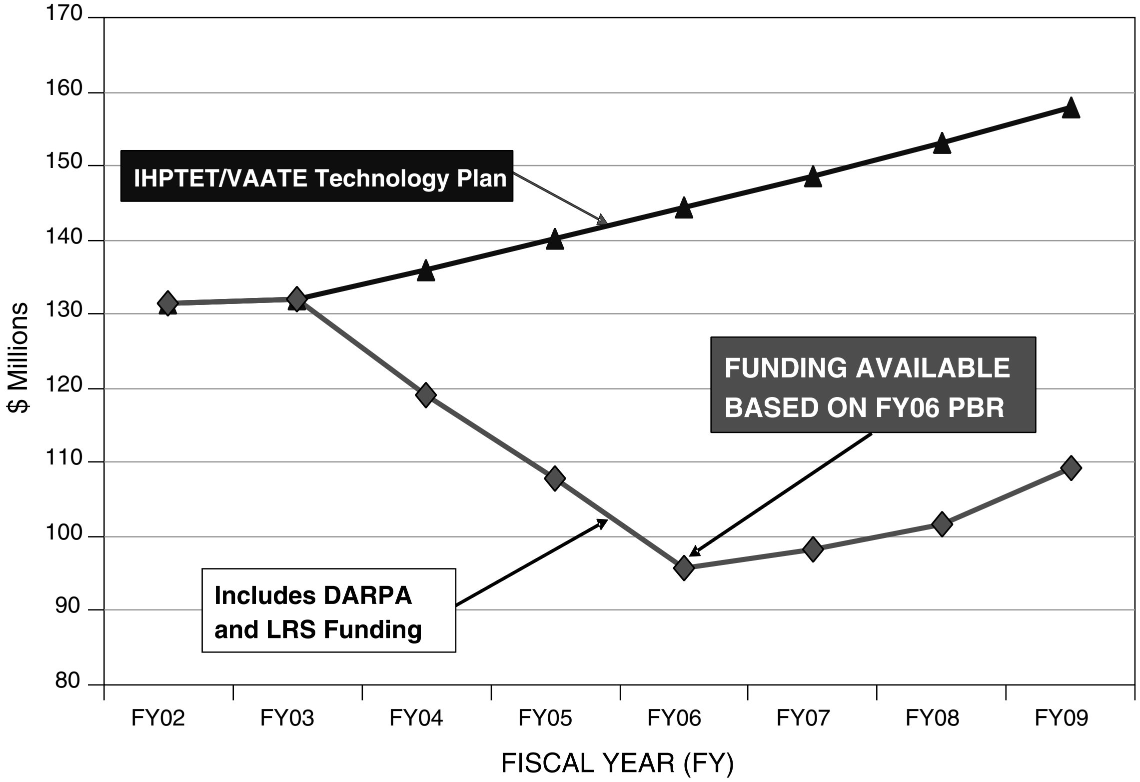


FIGURE 8-6 Turbine engine technology funding. PBR, President's Budget Request; DARPA, Defense Advanced Research Projects Agency; LRS, long-range strike. SOURCE: Burns (2005).

shown in Figure 8-6, owing to the near elimination of the NASA and ManTech programs and reduced funding for the VAATE program, the funding available in the United States for the development of gas turbine technology is approximately one-third of the funding that produced the technology for the F119, F135, and GE90 engine families. With its greatly reduced budget, VAATE will demonstrate full TRL 6 core and propulsion system demonstrations only once every 3 to 5 years.

> **Finding 8-5.** DoD's planned investment in VAATE is inadequate to sustain a minimally acceptable rate of advancement in U.S. gas turbine engine technology.

> **Recommendation 8-5.** The Air Force and DoD should restore turbine engine S&T funding to the original level necessary to execute the VAATE plan (with recommended changes), with particular emphasis on reinvigorating engine demonstration programs aimed at rendering new technologies ready for transition to fielded engines.

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9

Acquisition, Financing, and Support

INTRODUCTION

Re-engining (and its inherent fuel savings) has been the focus of several studies of large nonfighter aircraft. Perhaps the most studied aircraft is the B-52, the subject of countless DoD analyses. Despite these studies, no large nonfighter aircraft has ever been re-engined for fuel savings purposes only. Rather, the re-engining of aircraft in this category has been driven by mission requirements. A recent example of this is the decision to re-engine the C-5 to improve its operational performance, thereby increasing its mission capabilities. It is also important to note that even if an aircraft were to be re-engined to save fuel, the projected fuel savings might never materialize. In the case of the re-engining of the KC-135 fleet, for example, the re-engined aircraft were more fuel efficient and produced more thrust, and they could carry more fuel and support more missions. However, the Air Force never actually used any less fuel than it had before, because it flew the aircraft more. In addition, the cost of the re-engining program was increased by the costs of modifying the landing gear and of other modifications that were required to accommodate the increased weight of the new engines and the increased fuel loads that the aircraft became capable of handling.

The committee has concluded, upon review of the specifics of each study, that the aforementioned re-engining (fuel-saving) efforts failed for two main reasons:

- The requisite large initial investments were difficult to justify within the context of constrained budgets and competition for investments from projects having actual or perceived higher priority and
- Longer payback periods could not be exploited even if the aircraft was projected to remain in the active inventory for an extended period of time, because of legislative restrictions on obligating the government to expenditures (payback of upfront modification costs) that had not yet been appropriated.

When such issues arise in the private sector, commercial entities are able to finance these large investments through equity investments and bond offerings or by leasing the items in question on a long-term basis. The latter mechanism is most popular because the requisite initial investment is not included on the balance sheet as a single item but is spread out over the time during which the items will be used in the form of annual payments that can be appropriately budgeted for. However, long-term leases are seldom used by federal government departments and agencies because Congress is reluctant to approve financial arrangements that would restrict the appropriation prerogative of future congresses (CRS, 2003). However, Congress has overridden this precedent in cases where there are overwhelming benefits. Once such case is Defense Energy Support Center (DESC) long-term contracts for the supply of electrical power to military bases, whereby the government has been allowed to contract for electrical power for as long as 40 to 50 years to allow the amortization of new, more efficient power plants.

The current economic and geopolitical situation provides ample justification for the increased use of innovative acquisition, financing, and support mechanisms. The price of oil is forecast to continue to be at or near record highs, swelling the fraction of the DoD budget that is for the purchase of fuel and limiting the funding available for much needed improvements to the military facilities and equipment. Most of the oil that is consumed by the United States comes from locations that are both outside the United States and politically unstable, posing a risk to the U.S. economy and to national security. This economic and security risk is exacerbated by the fact that U.S. refining capacity and oil pipelines are both limited and geographically concentrated and therefore vulnerable to terrorist attacks. Some consequences of this situation were exemplified by the sharp increase in the price of fuel following the devastation of Hurricane Katrina. It is also important to note that more and more refined petroleum products are being imported, with the rate increasing as rapidly as the total amount of oil that is imported, because no refinery has been built in the United States since 1975. The result is that increasing amounts of foreign oil are shipped to foreign refineries before being shipped here, making U.S. energy sources all the more vulnerable.

The mechanisms presented in this section are designed to reduce oil consumption by providing innovative ways to acquire, finance, and support the increasing engine improvements or changes.

OVERVIEW OF OPTIONS

The committee identified 10 options for the acquisition, financing, and support of engine improvements and changes. Each option was categorized as an acquisition, financing, and/or support mechanism. The options then were partitioned into three further groups:

- In Group 1 are the options the committee believes the Air Force should adopt right away.
- In Group 2 are the options that the committee believes the Air Force should aggressively evaluate to determine their true utility.
- In Group 3 are the options that have traditionally not been implemented because they contravene U.S. government acquisition, financing, and support rules; they are included for completeness because they are mechanisms that would be used in the commercial sector.

The details of each option are provided below, along with a discussion of its benefits and its implementation challenges.

OPTIONS IN GROUP 1

The committee believes the Air Force should adopt the options in Group 1, summarized in Table 9-1, right away. Of the four options in this group, the committee finds that the first (maintain commercial derivative engines to Federal Aviation Administration (FAA) standards) and the second (fully compete

TABLE 9-1 Group 1: Options That Should Be Implemented Right Away

Option	Category	Expected Benefit(s)	Implementation Challenge(s)
1. Maintain all commercial derivative engines to FAA standards.	Support	Fuel savings. Performance improvements. Potential safety improvements. Reduced maintenance costs. Engines with residual value at the end of the lifetime of the airframe on which they will be mounted because they can be leased or sold in the commercial engine market when the airframe is retired.	Bringing the current military commercial derivative engines up to the commercial standards. Obtaining FAA certification for their use on commercial aircraft (since they have not been maintained to a common standard in the past).
2. Compete all maintenance contracts for all commercial derivative engines among all commercial and military maintenance facilities, and do not bundle purchase with maintenance.	Support	Assures that engine maintenance accounts for a smaller share of LCC. Reduces the net cost of the engines (including acquisition, operation, maintenance), increasing the likelihood of a positive NPV. May result in commercial entities doing more maintenance at Air Force depots, thereby increasing utilization of Air Force facilities.	
3. Create line item in the defense budget for the upgrading of engines and for the re-engining of large nonfighter aircraft.	Financing	Fixed amount available each year that is fenced off from other expenditures. Allows for better scheduling of upgrades and re-engining in relation to mission needs and nominal aircraft maintenance schedules. Facilitates maintenance of Air Force engines to FAA standards.	Congress must recognize that this is a proper operating expense rather than a capital expense. Requires significant discipline on the part of those creating and modifying the budget.
4. Implement a fuel savings performance contract strategy similar to the Energy Savings Performance Contract (ESPC) and Share-in-Savings (SiS) contracts currently being used in USAF facilities management and IT management.	Financing	Air Force benefits from aircraft with more fuel-efficient engines with no up-front capital expenses. Contractor compensated by sharing in the cost savings resulting from the use of more fuel-efficient aircraft.	May require specific statutory authority similar to the National Energy Conservation Policy Act for ESPCs and the E-Government Act for SiS contracts. May result in long contract and payback period due to high cost of fuel-efficient engines.

all maintenance contracts) are perhaps the most important as they are enablers of the subsequent options. To improve the business case for re-engining, the Air Force must have commercial derivative engines maintained to FAA standards if these engines are to be leased or sold after the airframes on which they are mounted have been retired (and also to increase their residual value). It must also ensure that engine maintenance costs contribute less to the life-cycle cost (LCC) by subjecting the maintenance contract to open competition, thereby reducing that particular cost component in net present value (NPV) calculations.

Option 1: Maintain All Commercial Derivative Engines to FAA Standards

The FAA sets airworthiness certification and safety standards for commercial engines and regulates the maintenance of these engines. To date, the Air Force has chosen to maintain its engines to its own standards. The committee believes that the Air Force should maintain all of its commercial derivative engines to FAA standards rather than to the equally demanding but different government standards currently used. This will allow the Air Force to benefit from the improvements that the FAA deems important based on problems that develop in commercial operation (typically in the area of safety) and the expenditures by commercial entities to improve performance (typically in the area of fuel consumption). Just as it makes good sense to buy commercial derivative engines for large nonfighter aircraft, it makes equally good sense to take advantage of commercial improvements in their engines and maintain military engines to the same standards.

Engines in the commercial fleet accumulate flying hours much faster than engines in the military fleet. If the engines in the military fleet were maintained to the same standards as the engines in the commercial fleet, the military would gain invaluable information on failure modes and required maintenance. Safety issues that arise in the commercial fleet could be dealt with much more rapidly and the benefits of commercial modifications realized much more quickly.

Commercial users are always interested in fuel savings and typically make several improvements to their engines to reap the fuel consumption benefits afforded by new technology. The Air Force would benefit from having an engine with the same configuration as nonmilitary users. The CFM56-2 engine on the KC-135R serves as an excellent example. When the KC-135 aircraft were re-engined with CFM56-2 engines, commercial users were operating the same engine. Today the KC-135 aircraft are still powered with CFM56-2 engines, while the commercial users are predominantly flying CFM56-7 engines. The CFM56-7 engines are 29 percent more fuel efficient than the CFM56-2 engines, and all of the nonrecurring engineering costs to develop and certify those modifications have been borne by the commercial users. In addition, the Air Force is paying a premium for obsolete CFM56-2 parts, at least for the parts that are not common to the -7 configuration.

There are other benefits to a common engine configuration, including the potential for creating a common pool of commercial/military engines and/or engine parts (to be discussed later in this chapter). Such a pool would allow the military to rely on commercial assistance with engines much as it does with transport aircraft through the Civil Reserve Air Fleet (CRAF) program. In addition, a common configuration for military and civilian engines would result in Air Force engines having some residual commercial value when no longer needed by the military, particularly since the military engines would have substantially fewer hours of flight time than commercial engines of comparable age. Finally, common engine fleets would allow the military to take advantage of common training of engine mechanics and facilitate the hiring or placement of needed or excess mechanics as inventories and workloads dictate.

The expected benefits include fuel savings, performance improvements, potential safety improvements, reduced maintenance costs, and engines with residual value at the end of the lifetime of the airframe on which they will be mounted.

The only implementation challenges are related to bringing the current military commercial derivative engines up to commercial standards and obtaining FAA certification for their use on commercial aircraft (since they were not maintained to a common standard in the past). That being said, there is no reason why the Air Force should not adopt a policy of maintaining all newly acquired commercial derivative engines to commercial standards in the future. It should also review the possibility of applying this policy to existing fleets wherever possible. The C-17's engines, for example, are overhauled in United Airlines' FAA-approved shops alongside United's commercial equivalent engines. However, the two engine lines are maintained to different standards, at a considerable cost to the government.

Option 2: Compete All Maintenance Contracts

Whenever the Air Force determines that the maintenance of an engine is to be contracted out, the maintenance contract should be competed across the entire maintenance, repair, and overhaul industry to maximize the effect of competition on price and to take advantage of economies of scale. When the Air Force decided to re-engine the C-5, each of the original equipment manufacturers (OEMs) proposed an engine and included in its proposal engine depot maintenance for the life of the engine. Thus, although the Air Force got bids for a new engine from virtually all the producers of engines, the competition for maintenance of the engines was by default limited to the OEMs, which maintain only a fraction of the commercial engines that are not under warranty. Most commercial users either maintain their own engines or contract maintenance, repair, and overhaul to a third-party commercial facility. The engine OEMs are the best in the world at designing and producing new engines, but they have proven to be very expensive when it comes to maintaining them. They also have a built-in conflict of interest when it comes to repairing or replacing parts with new parts made by their company unless there is a fixed price for maintenance of the engine. Even with a fixed price there is a problem in that no one knows what the engine will need in the future, and the engine manufacturers must cover all possibilities, making it difficult for them to share potential future savings from innovative production improvements or repair techniques. This fact has led to the development of Production Manufacturing Authorities (PMAs) and Designated Engineering Repairs (DERs) and their use by commercial users. PMAs and DERs are alternative manufacturing sources and repair schemes that are certified by the FAA to be equivalent to or better than the original manufacturer's parts. The nonuse of PMAs and DERs on military engines is one important reason the overhaul costs for Air Force C-17 engines in United Airlines' engine shops are higher than the overhaul costs for the Air Force's commercial equivalent engines in the same shops.

In addition, full and open competition may eliminate the middleman and save money. In the case of the C-17, the Air Force contracts for heavy maintenance of the aircraft with Boeing, which in turn contracts for engine overhaul support from Pratt & Whitney (P&W). P&W in turn contracts for engine overhauls from United Airlines. The Air Force should have openly competed the overhaul of the engines or required Boeing to do so and pass the saving to the Air Force. All of these competitions would, of course, be open to the engine OEMs as well, and they would have an equal opportunity to win the maintenance contract. An OEM may be able to offer marginal pricing if it has the engine in question in production or is still producing parts for the engine. In no case should the Air Force be worse off than it is today.

Finally, should the competition result in Air Force engines being maintained in a commercial shop or a commercial user teaming with the Air Force to overhaul its engines in an Air Force depot along with Air Force engines, commonality of engine configuration, recommended in Option 1, could more easily be maintained.

In summary, the expected benefits include (1) smaller share of LCC goes for engine maintenance,

(2) reduction in the net cost of the engines (including acquisition, operation, maintenance) and a correspondingly greater likelihood of a positive NPV, and (3) potential for commercial entities doing more maintenance at Air Force depots, thereby increasing the utilization of Air Force facilities.

Option 3: Create a Line Item in the Defense Budget

While there is common agreement on the benefits of engine modifications or re-engining (lower fuel consumption, better performance, reduced maintenance costs, etc.), such efforts have been stymied by the need for upfront procurement financing and the estimated long times for realizing the financial benefits of so doing.

Table 1-1 identifies and prioritizes those nonfighter platforms that are in need of, or would most benefit from, engine modification or re-engining, Those platforms that have more recent engines might benefit from engine modifications or re-engining 10 or more years from now as technology to improve engine performance is developed. Since military airframe lifetimes encompass a number of engine improvement cycles, an ongoing program for engine modification or re-engining should become an operational line in the Air Force budget.

To implement this proposal, the Air Force should annually determine the appropriate budget for engine modifications/re-engining for the portion of the nonfighter aircraft fleet that will be taken out of service for heavy maintenance that year. Every year the Air Force should prioritize the needs for that year. On this basis, by the time all the work suggested by Table 1-1 is completed, the platforms not in need of engine modification/re-engining would be ready to benefit from such action and would no longer need to be a line item in the defense budget.

This proposal for a line item can be implemented within existing Air Force and congressional budgetary practices. It would hasten lower fuel consumption, better engine and aircraft performance, and reduced maintenance costs. Also, if Option 1 is adopted, the engines might have residual value when they are no longer needed, an additional cost benefit.

In summary, the expected benefits include (1) having a fixed amount available each year that is fenced off from other expenditures, (2) better scheduling of upgrades and re-engining in relation to mission needs and nominal aircraft maintenance schedules, and (3) potential residual value as new Air Force engines are maintained to FAA standards as per Option 1.

The following implementation challenges have been identified: (1) Congress must recognize that this is a proper operating expense rather than a capital expense and (2) significant discipline is needed on the part of those creating and administering the re-engining budget.

Option 4: Implement a Fuels Savings Performance Contract Strategy

The financing issues discussed under Option 3 related to the challenges of aircraft re-engining initiatives. They included the lack of up-front funding and the inability to commit to a payback period beyond the congressional funding appropriations. Although these issues continue to hinder aircraft re-engining initiatives, for specific capital investments programs, such as energy and utilities investment projects, Congress has managed to provide specific authorities that overcome the challenges and allow for alternative approaches to financing capital investments. These alternative approaches to financing capital investment contracts do not require up-front congressional appropriations. They include Energy Savings Performance Contracts (ESPCs) and Share-in-Savings (SiS) contracts. Both approaches involve financing arrangements in which the contractor provides the up-front investment and is then compensated out of the resulting accrued savings or revenue.

The use of an ESPC acquisition strategy is authorized by the National Energy Conservation Policy Act (NECPA) (42 U.S.C. 8287).[1] This Act allows the use of an ESPC when it is LCC-effective, to reduce energy use and cost in an agency's facilities and operations. Executive Order 13123, Section 403, June 3, 1999, Greening the Government Through Efficient Energy Management, requires an agency to make maximum use of the authority provided by NECPA. The NECPA resulted in the establishment of Federal Acquisition Regulation (FAR) 23.204.[2]

The FAR also states that under an ESPC, an agency can contract with an energy service company for a period not to exceed 25 years to improve energy efficiency in one or more agency facilities at no direct capital cost to the U.S. Treasury. The energy service company finances the capital costs of implementing energy conservation measures and receives, in return, a contractually determined share of the cost savings that result (FAR 23.204). Although this authority seems to be specific to energy and utility systems such as water, sewer, and steam distribution systems as well as electricity and heating, ventilation, and air conditioning systems, the committee sees no reason why the concept should not be applicable to aircraft propulsion systems.

The use of an SiS acquisition strategy is authorized under the E-Government Act of 2002, Sections 210 and 317. This Act allows an agency to enter into an SiS contract for information technology (IT), in which the government awards a contract to improve mission-related or administrative processes or to accelerate the achievement of its mission and shares with the contractor savings achieved through contract performance. In addition, Congress has designated the General Services Administration (GSA) to play a leadership role in developing and institutionalizing the share-in-savings concept government-wide. The GSA has listed the following as the most prominent applications of SiS contracts: systems consolidation (e-government, payroll, data centers, reverse auctions), audit recovery (wireless communications, telephone lines), revenue enhancement (fee-based services), and unit price savings for recurring goods and services (reverse auctions).[3] Although the SiS acquisition strategy is specifically authorized for IT improvements to administrative processes, the concept might also be successfully applied to aircraft propulsion systems.

It should be noted that the congressional authority for ESPCs and SiS contracts is based on the use of an LCC analysis to determine the cost and benefits of the capital investment. Specifically, Executive Order 13123, Section 401, states as follows:

> Agencies shall use life-cycle cost analysis in making decisions about their investments in products, services, construction, and other projects to lower the Federal Government's costs and to reduce energy and water consumption. Where appropriate, agencies shall consider the life-cycle costs of combinations of projects, particularly to encourage bundling of energy efficiency projects with renewable energy projects. Agencies shall also retire inefficient equipment on an accelerated basis where replacement results in lower life-cycle costs. (FR, 1999, p. 6)

LCCs here are defined as the "sum of the present values of investment costs, capital costs, installation costs, energy costs, operating costs, maintenance costs, and disposal costs, over the lifetime of the project, product, or measure." (Additional guidance on measuring life-cycle costs is specified in 10 CFR 436.19.) LCC-effective means "the life-cycle costs of a product, project, or measure are estimated to be equal to or less than the base case (i.e., current or standard practice or product)." Additional guidance

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[1] For additional information on the NECPA, please see http://www.noresco.com/site/pdf/epa1992.pdf. Last accessed on January 22, 2006.

[2] For additional information on FAR 23.204, please see http://www1.eere.energy.gov/femp/pdfs/far_rule1201.pdf. Last accessed on January 22, 2006.

[3] Available online at http://www.gsa.gov.

on measuring cost-effectiveness is specified in 10 CFR 436.18 (a), (b), and (c), 436.20, and 436.21 (EO 13123, Sections 707 and 708).[4]

It would seem feasible, based on the success of ESPC and SiS contracts for energy and utility systems, to request specific congressional authority for aircraft propulsion systems. The use of "fuel savings performance contracts" (FSPCs) would apply the "contractor compensation by savings" concept to aircraft re-engining contracts. If an FSPC acquisition strategy is proven to be LCC-effective (in accordance with the statutes), the Air Force could be allowed to award long-term contracts to aircraft/engine contractors. These contractors, providing their own up-front capital investment, would re-engine the aircraft with more fuel-efficient engines and be compensated by sharing the accrued savings or revenues resulting from the improved fuel efficiency and/or reduced maintenance cost of the aircraft. Of course, the payback period for FSPCs may be significantly longer than the less-capital-intensive ESPCs or SiS contracts. However, this may be offset by the increase in savings and revenues realized by the Air Force and shared with the contractor. With the use of FSPCs, the financial challenges of having no up-front government funding and of Congress's inability to commit to a payback period beyond the congressional funding appropriations period would appear to be resolved.

With this approach, (1) the Air Force benefits from aircraft with more fuel-efficient engines and no up-front capital expenses and (2) the contractor is compensated from the cost savings resulting from the use of more fuel-efficient aircraft.

Implementation challenges are twofold: (1) FSPC may require specific statutory authority similar to the NECPA for ESPCs and the E-Government (E-Gov) Act for SiS contracts and (2) it may result in long contract and payback periods owing to the high costs of fuel-efficient engines.

> **Recommendation 9-1.** The Air Force should adopt the following options right away: (1) maintaining all commercial derivative engines to FAA standards, (2) competing all maintenance contracts, (3) creating a line item in the defense budget, and (4) implementing a "fuel-savings performance contract" strategy.

OPTIONS IN GROUP 2

The committee believes the Air Force should aggressively evaluate the options in Group 2, summarized in Table 9-2, to determine their true utility.

Option 5: Re-engine Air Force Aircraft with Commercial Engines and Lease or Resell the Engines When the Airframe Is Retired

In this option, the Air Force re-engines its existing aircraft with engines that are expected to be widely used in the commercial fleet beyond the planned retirement date of the Air Force airframes on which they will be mounted, then leases or resells the engines upon airframe retirement. The expectation that an engine will be widely used beyond the planned retirement date of the Air Force airframe is an important component of this approach, as the future demand for an engine type is a key determinant of the residual value for that engine type. Another determinant of residual value is the maintenance history. Thus, as noted under Option 1, the Air Force would be required to maintain its engines to commercial standards. As a variation on this approach, the Air Force could offset a portion of the re-engining cost up

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[4] Part 436 of the Code of Federal Regulations may be found online at http://www.wbdg.org/pdfs/10cfr436.pdf. Last accessed on January 23, 2007.

TABLE 9-2 Group 2: Options That Should Be Aggressively Explored

Option	Category	Expected Benefit(s)	Implementation Challenge(s)
5. Re-engine Air Force large nonfighter aircraft with commercial engines and maintain these engines to FAA standards in an FAA-certified Air Force depot or in an FAA-certified commercial maintenance facility.	Acquisition and support	Engines will have residual value at the end of the lifetime of the airframe on which they are mounted because they can be leased or sold in the commercial engine market when the airframe is retired. Residual value of engine can be included in the NPV calculation used to justify the re-engining of the airframe in question, reducing the net cost of the engines and increasing the likelihood of a positive NPV.	Limits candidate engines to those that are available in the commercial sector, which may (though this is unlikely given the broad capabilities of commercial engines) have an impact on Air Force ability to meet mission requirements. Requires changes to current Air Force maintenance scheduling practices as engine upgrades would need to be done in accordance with FAA airworthiness directives. May require additional training for staff and changes to record-keeping practices at Air Force depots.
6. Create a joint commercial–military spare engine and engine parts pool.	Acquisition and support	Reduces the number of engines and engine parts that have to be kept in reserve to ensure war readiness due to conflicts between commercial and military needs, as well as the general non-correlation of maintenance failures among a large number of engines. Provides a mechanism for the alternative use of engines when they would otherwise not be used by the Air Force because the airframe to which they are mounted is in the depot for extended overhaul. Increases the effective utilization of the spare engines and parts.	Requires Option 1 and therefore has all the implementation challenges of Option 1. Air Force must have priority access to spare engines and parts in times of national need in a similar fashion to CRAF.
7. Long-term (multiyear) lease of commercial engines that are maintained to FAA standards by the lessor in an FAA-certified Air Force depot, or in an FAA-certified commercial maintenance facility.	Acquisition, financing, and support	Air Force has no significant initial capital outlay. Lessor retains residual value of engine at the end of the lifetime of the airframe on which they will be mounted because they can lease or sell the engines in the commercial engine market when the airframe is retired. Air Force gets best possible leasing rate (equivalent to treasury borrowing rate) because the long-term nature of the lease arrangement ensures that there is negligible expected cost of having to hold the engine in stock while a new lessee is identified.	Air Force would still have to pay for any required modifications to the airframe. Air Force would not own the engines, which might be a concern for Congress. Congressional approval would be required for multiyear leasing arrangement; however, there is a precedent for the granting of a waiver as per the DESC multiyear contracts. Has all the implementation challenges of Option 1 because engines would be commercial engines. Would require coverage for termination liability should the airframe be retired earlier than planned.

8. Short-term (yearly) lease of commercial engines that are maintained to FAA standards by the lessor in an FAA-certified Air Force depot, or in an FAA-certified commercial maintenance facility.	Acquisition, financing, and support	Air Force has no significant initial capital outlay. Does not require a multiyear agreement. Air Force has option to forgo future leasing. Lessor retains residual value of engine at the end of the lifetime of the airframe on which they will be mounted because it can lease or sell the engines in the commercial engine market when the airframe is retired.	Air Force would still have to pay for any required modifications to the airframe, Air Force would not own the engines, which might be a concern for Congress. Air Force would incur a premium for having the flexibility to forgo future leasing at the end of each year, but any such premium would be small because the engines would be commercial engines and could therefore be leased or sold in the commercial market should the Air Force exercise the option not to continue leasing them; thus, the premium would be equal to the expected holding cost. Has all the implementation challenges of Option 1 because engines would be commercial engines.

front by selling a forward contract for the delivery of the engines at a specified future date (the planned airframe retirement date).

The primary difference between this approach to purchasing engines and prior approaches is that the engines are treated separately from the airframe on which they will be mounted in recognition of the fact that the engines are themselves commodities that can be traded or resold in the commercial marketplace. It is also interesting to note that the adoption of such an approach could also change the way the Air Force thinks about the retirement of airframes. Specifically, the effects of acquisition decisions on the residual value of the engines in the fleet could become a factor in the decision-making process, as delays in airframe retirement would have a measurable cost.

The expected benefits of this approach are as follows: (1) the engines will have residual value at the end of the lifetime of the airframe on which they are mounted because they can be leased or sold in the commercial engine market when the airframe is retired and (2) the residual value of the engine can be included in the NPV calculation used to justify the re-engining of the airframe in question, thereby reducing the net cost of the engines and increasing the likelihood of a positive NPV.

Envisioned implementation challenges are these: (1) candidate engines would be limited to those that are available in the commercial sector, which may (though this is unlikely given the broad capabilities of commercial engines) have an impact on Air Force ability to meet mission requirements, (2) current Air Force maintenance scheduling practices would have to be changed so that engine upgrades could be done in accordance with FAA airworthiness directives, and (3) additional training might be required for staff, and changes would be required to record-keeping practices at Air Force depots.

Option 6: Create a Spare Engine and Parts Pool

With Option 6, the Air Force would re-engine existing aircraft with commercial derivative engines and also participate in a commercial spare engine and parts pool. The benefits of this approach are that (1) an engine that would otherwise be sitting in the shop while the military airframe to which it was nominally attached was being overhauled could be loaned for use on a commercial aircraft that is in need of a spare engine and (2) the Air Force could borrow engines when one of its aircraft needs a spare engine. The net effect of this arrangement is that the total number of spare engines required for both the commercial and military fleet would be reduced because the more effective use of spare engines would reduce the time engines spend off-wing. The committee found examples of this approach in the commercial airline industry.

The expected benefits include (1) a reduction in the number of engines and engine parts that have to be kept in reserve to ensure war readiness in the face of conflicting commercial and military needs, as well as the general noncorrelation of maintenance failures in a large number of engines, (2) a potential alternative use of engines when they would otherwise not be used by the Air Force because the airframe on which they are mounted is in the depot for extended overhaul, and (3) an increase in the effective utilization of the spare engines and parts.

Envisioned implementation challenges include (1) all the implementation challenges of Option 1, which is required, and (2) the creation of a law or agreement whereby the Air Force, like the CRAF, has priority access to spare engines and parts in times of national need.

Option 7: Lease Engines on a Long-Term Basis

A lease is an agreement in which one party gains a long-term rental and the other party gains a form of secured long-term debt. That is, the lessee gains a long-term contract for the use of an asset, and the lessor is assured of regular payments for a specified number of years. Entering into a simple lease is equivalent to purchasing an asset using secured debt to fund the purchase while simultaneously selling a forward contract to deliver the asset at some specified future date; and a lease with an end-of-term option to buy is equivalent to entering into a simple lease and simultaneously purchasing a European-style call option on the leased asset. A lease with an end-of-term option is also financially equivalent to outright purchase coupled with purchase of a European-style put option on the asset.

Long-term leasing is a common commercial practice that is becoming even more prevalent, with many commercial users of aircraft and aircraft engines (the airlines) leasing these assets from manufacturers, leasing agencies, or other nonoperating owners. International Leasing and Finance Corp. and General Electric Commercial Aircraft Services are two of the largest owners of aircraft even though neither is an operator. Leases are used for a variety of purposes beyond simple financing that can include removing debt from a balance sheet and driving an expenditure to be classified as an operating expense rather than a financing cost (Gorton and Souleles, 2005). The committee did not consider these alternative uses.

As part of its effort, the committee reviewed the Congressional Research Service's 2003 report on the KC-767 Tanker Lease Proposal as well as several presentations on the various commercial power-by-the-hour engine leasing programs that it received from industry (CRS, 2003). The KC-767 tanker lease proposal, which would have involved 6-year leases on KC-767 tanker aircraft, with an option to purchase at lease end, ultimately failed to receive congressional approval.

While there is no sound economic argument prohibiting long-term leasing as a means of financing a re-engining program, long-term leases have the drawback of obligating future Congresses to commit funds to the lease payments and, in this sense, are similar to multiyear procurement arrangements. However, long-term leasing represents a fair and viable means of financing a re-engining program, and as such should be aggressively evaluated by the Air Force.

The expected benefits are threefold: (1) the Air Force has no significant initial capital outlay, (2) the lessor retains residual value of engines at the end of the lifetime of the airframe on which they will be mounted because it can lease or sell the engines in the commercial engine market when the airframe is retired, and (3) the Air Force gets the best possible leasing rate (equivalent to the Treasury borrowing rate) because the long-term nature of the lease arrangement ensures that there is negligible expected cost of having to hold the engine in stock while a new lessee is identified.

The following implementation challenges have been identified: (1) the Air Force would still have to pay for any required modifications to the airframe, (2) it would not own the engines, which might be a concern for Congress, (3) congressional approval would be required for a multiyear leasing arrangement (however, there is a precedent for the granting of a waiver as per the DESC multiyear contracts), (4) this approach has all the implementation challenges of Option 1, because the engines would be commercial engines, (5) this approach would require coverage for termination liability should the airframe be retired earlier than planned, and (6) engines might have little or no residual value depending on how extensively they are still being used in the commercial fleets.

Option 8: Lease Engines on a Short-Term Basis

As an alternative to the long-term lease option described above, the Air Force could consider acquiring engines for re-engined aircraft via short-term leases, fee-for-service arrangements, or other similar rental arrangements. These arrangements could vary from short-term rental agreements under which the Air Force leases the engine but performs all maintenance and repairs organically, to fee-for-service arrangements under which the leasing company is responsible for providing not only the engine but all associated maintenance and repair activities. They could even be structured as longer-term leases with an annual option to cancel the lease. Regardless of the particulars, all such arrangements would only require the U.S. government to make yearly spending commitments. Unlike longer-term leases, there would be no multiyear spending requirement. Even if the Air Force took more than a year to decide to cancel a yearly lease, the fact that the lease is yearly would mean that the Air Force would always be able to cancel the lease the same year it finally decided to cancel.

The expected benefits of short-term leasing include these: (1) the Air Force has no significant initial capital outlay, (2) no multiyear agreement is needed, (3) the Air Force has the option to forgo future leasing, and (4) the lessor retains residual value of the engines at the end of the lifetime of the airframe on which they are mounted because it can lease or sell the engines in the commercial engine market when the airframe is retired.

The last benefit listed above is particularly important. Because Air Force aircraft fly so few hours annually, the engines of re-engined aircraft are likely to significantly outlast the airframes, giving the engines residual value at the end of their use by the Air Force. Even if the Air Force elects to terminate a yearly lease, the leasing company is likely to be able to place the engines in the commercial market and recover their residual value. As a result, a properly structured short-term leasing option would give the Air Force a way to purchase only the fraction of the life of an engine that it actually uses. This could significantly improve the business case for almost all platforms considered in this study.

The following implementation challenges have been identified: (1) the Air Force would still have to pay for any required modifications to the airframe, (2) the Air Force would not own the engines, which might be a concern for the Air Force and for Congress, (3) the Air Force would incur a premium for having the flexibility to forgo future leasing at the end of each year, but any such premium would be small—probably equal to the expected holding cost—because the engines would be commercial engines and could therefore be leased or sold in the commercial market should the Air Force choose not to continue leasing them, and (4) this approach has all the implementation challenges of Option 1 because the engines would be commercial engines.

Because short-term leases are not commonly used by the Air Force, many of the identified challenges are likely to be cultural challenges more than anything else. For example, while (3) in the preceding paragraph might seem like a challenge, it is simply a reflection of the fact that a short-term lease gives the Air Force more flexibility than any other alternative and that there is financial value in having this option. Similarly, while (2) above might seem like a concern at first, the fact that the Air Force would physically control the engines (they are mounted on the Air Force aircraft to which they are assigned) makes it difficult to imagine that they would not be available in a contingency. Challenge (4), however, does represent a very real challenge. For short-term leases, as envisioned in this chapter, to benefit the Air Force, it would be necessary to ensure that the engines retain their commercial value, and this would lead to the same issues identified earlier.

Overall, leasing engines on a short-term basis appears likely to provide the Air Force with all of the benefits of a longer-term lease without forcing it or the Congress to make multiyear purchasing commitments. For this reason, the committee recommends that the Air Force aggressively evaluate this approach further to determine if it would indeed be useful.

> **Recommendation 9-2.** The Air Force should aggressively evaluate the following options to determine their true utility: (1) re-engining Air Force aircraft with commercial engines and leasing or reselling the engines when the airframe is retired, (2) creating a spare engine and parts pool, (3) leasing engines on a long-term basis, and (4) leasing engines on a short-term basis.

OPTIONS IN GROUP 3

In keeping with the statement of task admonition to develop re-engining implementation strategies, including conventional as well as innovative acquisition, financing, and support concepts, the following additional options were identified by the committee. These options were identified because they reflect innovative, outside-the-box thinking, not because the committee has already determined them to have value. Summarized in Table 9-3, they are included here to reflect completeness in the committee's discussion of the various re-engining approaches. Determining the feasibility of implementing these innovative options in the post-9/11 environment and during the Global War on Terrorism will require additional in-depth analysis and discussion.

Option 9: Sale and Leaseback on a Long-Term Basis

Under a sale-and-leaseback arrangement, a party sells assets it owns to a counterparty and then leases these same assets back from the counterparty. Typically, the leasing agreement is long-term. Sale-and-leaseback arrangements are often used for a variety of nonfinancing purposes, including removing debt from a balance sheet. The committee did not consider these alternative uses. Rather, it considered the

TABLE 9-3 Group 3: Options That Might Be Explored

Option	Category	Expected Benefit(s)	Implementation Challenge(s)
9. Sell aircraft that are to be re-engined for a nominal price to a commercial entity with the stipulation that they pay for the new engines and the required changes to the airframe, and then lease the enhanced aircraft to the Air Force on a long-term (multiyear) basis.	Acquisition and financing	Air Force does not have to pay for any required modifications to the airframe. Air Force has no significant initial capital outlay. Lessor borrows capital at best possible rate (equivalent to Treasury borrowing rate) because of the long-term nature of the lease arrangement.	Air Force would not own the aircraft, which might be a concern for the Air Force and for Congress. Congressional approval would be required for multiyear leasing arrangement; however, there is a precedent for the granting of a waiver as per the DESC multiyear contracts. OMB accounting rules may have to be modified so that the money that is borrowed by the lessor does not count against the Treasury borrowing limit.
10. Sell aircraft that are to be re-engined for a nominal price to a commercial entity with the stipulation that they pay for the new engines and the required changes to the airframe, and then lease the enhanced aircraft to the Air Force on a short-term (yearly) basis.	Acquisition and financing	Air Force does not have to pay for any required modifications to the airframe. Air Force has no significant initial capital outlay. No multiyear agreement is required. Air Force has the option to forego future leasing.	Air Force would not own the aircraft, which might be a concern for the Air Force and for Congress. Air Force would incur a premium for having the flexibility to forgo future leasing at the end of each year. This premium would be noticeable because the market for used Air Force large nonfighter aircraft is small. OMB accounting rules may have to be modified so that the money that is borrowed by the lessor does not count against the Treasury borrowing limit.

approach whereby the Air Force would sell the aircraft to be re-engined to a counterparty, which would then pay for the re-engining of the aircraft (adding value to the asset) and would thereafter lease the upgraded aircraft back to the Air Force. Thus, instead of leasing just the engines, the Air Force would be leasing whole aircraft. As considered in this study, sale-and-leaseback arrangements would involve only transfer of ownership of the aircraft. The Air Force would continue to house and operate the re-engined aircraft and, as such, would retain physical control of the assets.

As with a straightforward, long-term leasing arrangement, this approach has the drawback of obligating future Congresses to commit funds to the lease payments and, in this sense, is similar to multiyear procurement arrangements (CRS, 2003). That being said, a sale-and-leaseback arrangement is a fair and viable means of financing a re-engining program. In particular, unlike all other the arrangements considered above, it has the advantage of allowing the Air Force to realize the NPV of positive-NPV re-engining options as up-front cash that could be used to fund other acquisition programs, such as, the F-22, the Joint Striker Fighter, or space radar.

The expected benefits include these two: (1) the Air Force does not have to pay for any modifications to the airframe and (2) it has no significant initial capital outlay. Both of these benefits are the result of the fact that the Air Force is "selling" the asset to the counterparty and receiving cash up front in exchange for a commitment to make regular lease payments over a longer term. Any costs to the leasing company associated with modifications to the airframe or purchase of the engines from an OEM would be embedded as a discount in the sale price. In this way, the government would avoid all up-front outlays. Furthermore, the cost savings associated with the improved fuel efficiency of the leased aircraft could be converted into cash up front by attaching a premium to the sale price. This premium would lead to an increase in the lease payment that exactly offsets the dollar savings in fuel and maintenance costs enabled by re-engining. So, in annually paying the sum of the lease cost and the new annual fuel expense, the Air Force would be paying an amount identical to the corresponding annual operating and ownership costs prior to the re-engining, but it would also receive a large cash payment up front equal to the NPV savings associated with re-engining.

Three implementation challenges have been identified: (1) the Air Force would not own the aircraft, which might be a concern for it and for Congress, (2) congressional approval would be required for a multiyear leasing arrangement despite the precedent set by the DESC multiyear contracts for the granting of a waiver, and (3) owing to the long-term nature of the lease, OMB accounting rules might have to be modified so that the money that is borrowed by the lessor does not count against the Treasury borrowing limit.

The reader will note that this option faces essentially the same challenges faced by the long-term lease option described earlier. This is, of course, because the arrangement is, at its core, a long-term lease. Furthermore, in addition to the challenges listed above, the sale-and-leaseback approach also faces the challenge that it is the most unfamiliar and forward-leaning of the innovative approaches considered in this chapter. As such, it might face significant cultural resistance despite its potential benefits.

Overall, the committee determined that sale-and-leaseback arrangements could represent a fair and viable means of financing a re-engining program; and that, uniquely among the options considered, such arrangements allow up-front realization, in cash, of the benefits of re-engining. As such, the committee considered them necessary to a complete discussion of available options.

Option 10: Sale and Leaseback on a Short-Term Basis

As a variation of Option 9 above, the Air Force could finance re-engining by entering into a sale-and-leaseback arrangement built around an annual lease or other short-term rental of the re-engined aircraft rather than a long-term lease. This arrangement would allow the Air Force to reap the benefits of a sale-leaseback arrangement while avoiding a multiyear purchasing commitment. It would, of course, still face the same cultural obstacles described earlier.

The specific expected benefits of this approach are four in number: (1) the Air Force does not have to pay for any required modifications to the airframe, (2) it has no significant initial capital outlay, (3) no multiyear agreement is needed, and (4) the Air Force has an option to forgo future leasing. Again, the first two benefits are the result of the fact that the Air Force is selling the asset to the counterparty, so any costs to the leasing company associated with modifications to the airframe or purchase of the engines from an OEM can be embedded as a discount in the sale price. In this way, the government would avoid all up-front outlays. However, by engaging in a rental arrangement rather than a long-term lease, it could be possible to go one step further by embedding all of the leasing payments themselves into a further discount on the sale price. If the leasing company can generate sufficient revenue from the re-engined aircraft when they are not being used by the Air Force, either after termination of the short-term lease or while under lease but not being used by the Air Force, this revenue could offset lease payments. As a result, it is conceivable that the Air Force could embed all airframe modification costs, engine purchase costs, and lease payments into a discount on the sale price of the platform and still end up with a positive sale price. Under such a circumstance, the Air Force would be able to reap the benefits of re-engining with no up-front costs and no recurring costs.

The following implementation challenges have been identified: (1) the Air Force would not own the aircraft, which might be a concern for the Air Force itself or for Congress, and (2) it would incur a premium for having the flexibility to forego future leasing at the end of each year, and this premium would be sizable because the market for used Air Force large nonfighter aircraft is small.

The reader will note that this option faces essentially the same challenges faced by the short-term lease options described earlier. Furthermore, like sale-and-leaseback on a long-term basis, this option may, due to its unfamiliarity, face cultural resistance despite its potential benefits. Such resistance might be especially strong if the arrangement permits the leasing company to operate the aircraft when it is not being used by the Air Force, it would mean that the aircraft are not under the direct physical control of the Air Force for some period, potentially creating both International Traffic in Arms Regulations issues and the risk of unavailability during a contingency. However, these risks are, of course, no different than those faced by, for example, the United Kingdom in its proposed AirTanker lease.[5]

Air Force modifications to aircraft leased short term—e.g., communications relay packages and sensor systems—might present an additional logistical challenge as these systems would have to be removed from the aircraft at the end of the leasing period at what might be a significant cost relative to the duration of the lease. This removal cost might be reduced by designing the communication relay packages and sensor systems to be more readily removable. This might require changing the way they are connected together and mounted within the airframe, thus impacting their functionality. Any short-term leasing evaluation must therefore consider the cost of removing such packages and systems, which is likely to be significant. That being said, care must be taken not to overestimate this cost, as there is a nonzero probability that the short-term leases will be renewed and the removal of said equipment will not be necessary. Thus, an expected value for the removal cost must be derived.

Despite the potential challenges, the privatization of the Air Force's depot at Kelly Air Force Base sets a precedent for the approach described here. Furthermore, this option could make a great deal of

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[5] For additional information on the issues surrounding the AirTanker, please see the following Internet articles: (1) "British AirTanker Deal May Go Private," available online at http://www.defenseindustrydaily.com/2005/03/british-airtanker-deal-may-go-private/index.php, and (2) "Britain Air Tanker Deal Delayed Until Late 2006: Report," available online at http://www.defensenews.com/story.php?F=1531164&C=airwar. Articles last accessed on January 22, 2007.

sense for platforms such as the KC-135, which could be operated part-time by a leasing company as cargo aircraft. By entering into a sale-and-leaseback arrangement with a short-term or cancelable lease, the Air Force would be able to recover value from an asset that it would otherwise place in a boneyard.

Overall, the committee determined that sale-and-leaseback arrangements that use short-term leases could represent a fair and viable means of financing a re-engining program and that, of the options considered, they have the best potential to benefit the Air Force because they can enable up-front realization, in cash, of the benefits of re-engining without requiring any up-front or recurring spending. As such, it considered such arrangements a necessary part of a complete discussion of available options. However, the approach is also the most exotic of those considered and would be the most likely to face significant cultural resistance.

> **Recommendation 9-3.** The Air Force should analyze the following options in greater depth to determine their feasibility: (1) sale-and-leaseback on a long-term basis and (2) sale-and-leaseback on a short-term basis.

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Appendixes

Appendix A

Biographical Sketches of Committee Members

Kenneth E. Eickmann, *Chair* (Air Force, retired), whose leadership accomplishments include having led the federal rescue and recovery efforts following the 1995 bombing of Oklahoma City's Alfred P. Murrah Building, served as the director of the Construction Industry Institute (CII) at the University of Texas (UT) at Austin from June 1998 to October 2003. CII, a nonprofit research institute, is the principal national forum for the multitrillion-dollar-a-year construction industry. The more than 100 member companies of the institute are dedicated to improving the cost, schedule, quality, safety, security, and operability of constructed facilities. CII annually funds $5 million in research at 30 U.S. universities to improve the total quality and cost effectiveness of the construction industry. General Eickmann's recent accomplishments include selection as a distinguished engineering graduate of the University of Texas; selection for membership of the National Academy of Construction; selection as chairman of a General Officer Red Team, formed to review the logistics transformation efforts of the U.S. Air Force; and selection to serve on a National Research Council committee formed to evaluate the feasibility of achieving the science and technology requirements implied in the National Aerospace Initiative. He completed 22 assignments, including a stint from 1994 to 1996 as commander, Oklahoma City Air Logistics Center, Tinker Air Force Base. His last assignment on active duty was commander, Aeronautical Systems Center, Wright-Patterson Air Force Base. As commander, he chaired a consortium partnering the U.S. Department of Defense, the aerospace industry, and the Massachusetts Institute of Technology to increase competitiveness in the aerospace industry. General Eickmann currently serves as the vice chairman of the Texas Engineers' Task Force on Homeland Security and recently formed an executive placement company, The Eickmann Group, dedicated to the placement of retired military leaders in industry. General Eickmann earned a B.S. in mechanical engineering from UT Austin in 1967, an M.S. in systems engineering from the Air Force Institute of Technology in 1968, and is a graduate of the University of Michigan Executive Business Program and the John F. Kennedy School of Government at Harvard University. He has expertise in propulsion engineering, materials science and engineering, military systems acquisition, and systems engineering.

Natalie W. Crawford (NAE), *Vice Chair*, is vice president of the RAND Corporation and director of Project Air Force (PAF). It is her responsibility to ensure that the research agenda PAF addresses each year reflects those problems of greatest enduring importance to the Air Force, and that the research is of the highest possible quality and responsiveness. In addition, she must ensure that the PAF workforce is not only matched to the Air Force's research needs but that it is renewed. She has worked at the RAND Corporation for 40+ years and has deep, substantive technical and operational knowledge and experience in areas such as conventional weapons, attack and surveillance avionics, fighter and bomber aircraft performance, aircraft survivability, electronic combat, theater missile defense, force modernization, space systems and capabilities, and nonkinetic operations. She was a member of the Air Force Scientific Advisory Board since 1988 and was its vice chair in 1990 and co-chair from 1996 to 1999. She has served on numerous advisory committees. She received the Air Force Analytic Community's Lifetime Achievement Award and the Vance R. Wanner Memorial Award from the Military Operations Research Society in 2003. She received the Department of the Air Force Decoration for Exceptional Civilian Service in 2003 and 1995. Mrs. Crawford has a B.A. in mathematics from UCLA, where she also pursued graduate study in applied mathematics and engineering.

Dilip R. Ballal graduated from the Cranfield Institute of Technology with a Ph.D. in mechanical engineering. Currently, he is head of the Energy and Environmental Engineering Division at the University of Dayton. As division head, Dr. Ballal has overall responsibility for the direction and successful completion of basic and applied research in aerospace fuel science, fuels engineering, combustion, environmental engineering, modeling and simulation, and energy conservation. He joined the university in April 1983 as the leader of aerospace fuels and combustion group in the Research Institute. He has over 35 years of research experience in academia and industry. Dr. Ballal is also the Hans von Ohain Distinguished Professor in mechanical and aerospace engineering and director of the von Ohain Fuels and Combustion Center at the University of Dayton. His expertise in fuels, combustion, and emissions requirements of advanced propulsion systems has led to improvements in gas turbine combustor technology.

Meyer J. Benzakein (NAE) received a B.S. in mechanical engineering in 1960. He received an M.S.M.E. in 1963 and a Ph.D. in engineering mechanics in 1967. He joined General Electric in 1967. There he served in a number of positions in advanced technology and project and product engineering. He led the CFM56 engineering program from 1984 to 1993 and the GE90 engineering program from 1993 to 1995. In February 1995, Dr. Benzakein became general manager for engine systems design and integration, in which capacity he was responsible for engineering leadership and technical oversight of GE-Evendale's commercial and military aircraft engines. In January 1996, Dr. Benzakein took over the position of general manager, Advanced Engineering Programs. He maintained that position until he retired, in October 2004. He was responsible for leading the technology development efforts and the new commercial and military engines development programs. In January 2005, Dr. Benzakein joined the faculty of Ohio State University, where he is currently chair of the Aerospace Engineering Department and co-director of the Ohio Center for Advanced Propulsion and Power. Dr. Benzakein's experience on NAS committees includes membership on the Division on Engineering and Physical Sciences (DEPS) Aerospace Engineering Peer Committee, the DEPS Committee on Review of NASA's Next Generation Launch Technology program, and the Transportation Research Board (TRB) Committee for developing an aviation environmental design tool. Dr. Benzakein received the Gold Medal Award from the Royal Aeronautical Society in 2001. He was elected as a fellow of the Royal Aeronautical Society in 2002 and a fellow of the American Institute of Aeronautics and Astronautics (AIAA) in 2004.

John-Paul B. Clarke is an associate professor in the School of Aerospace Engineering at the Georgia Institute of Technology, where his research and teaching address optimization and robustness in aircraft and airline operations, air traffic management, and the environmental impact of aviation. He received S.B., S.M., and Sc.D. degrees from the Massachusetts Institute of Technology and was a faculty member there prior to moving to Georgia Institute of Technology. He has also been a researcher at the NASA Jet Propulsion Laboratory and a visiting scholar at the Boeing Company. Dr. Clarke is a member of the Airline Group of the International Federation of Operations Research Societies, the AIAA, the Institute for Operations Research and the Management Sciences, the Institute of Navigation, and Sigma Xi, the Scientific Research Society. He serves on several national and international committees, including the Aeronautics and Space Engineering Board (ASEB) of the National Research Council, the FAA Research Engineering and Development Committee, the Airspace Systems Program Subcommittee of the NASA Aerospace Research Advisory Committee, the AIAA Air Transportation Systems Technical Committee, and the Aircraft Noise Committee of the Society of Automotive Engineers. Dr. Clarke was the first director of the Partnership for Air Transportation Noise and Emissions Research (PARTNER), the Center of Excellence for Aviation Noise and Aircraft Emissions Mitigation, and is an active researcher in both PARTNER and the National Center of Excellence for Aviation Operations Research. In 1999, he was awarded the AIAA/American Association of Airport Executives (AAAE)/Airport Consultants Council (ACC) Jay Hollingsworth Speas Airport Award, and in 2003 he was awarded the FAA Excellence in Aviation Award.

David E. (Ed) Crow (NAE) graduated from the University of Missouri-Rolla with a Ph.D. in mechanical engineering. Dr. Crow joined the faculty of the University of Connecticut as a distinguished professor-in-residence in the mechanical engineering department after a distinguished career in industry. He joined Pratt & Whitney in 1966, rising to the position of senior vice president of Pratt & Whitney's engineering organization, where he was responsible for the design, development, validation, and certification of all Pratt & Whitney large commercial engines, military engines, and rocket products. He also led the research and development of advanced technologies systems to meet future aircraft requirements. Dr. Crow previously held the position of senior vice president for Pratt & Whitney's large commercial engines organization, which included the PW4000 and JT9D high-thrust family of products. Dr. Crow is a past secretary of the Society of Automotive Engineers (SAE), and a member of both the American Society of Mechanical Engineers (ASME) and AIAA. In addition to having served as president of Pi Tau Sigma, he has served on the Engineering Advisory Board at Clarkson University and is an elected member of the Academy of Mechanical Engineers at the University of Missouri-Rolla. His expertise is in propulsion engineering, thermodynamics, aerodynamics, systems engineering, and rocket propulsion engineering.

Alan H. Epstein (NAE) received B.S., M.S., and Ph.D. degrees in aeronautics and astronautics from the Massachusetts Institute of Technology. He is currently the R.C. Maclaurin Professor of Aeronautics and Astronautics at MIT and the director of MIT's Gas Turbine Laboratory. His responsibilities include teaching and research in aerospace propulsion, fluid mechanics, power production, and microelectromechanical systems (MEMS). He has been an active consultant to industry and government for over 25 years. His activities have included gas turbine design and operation, MEMS, system testing and advanced instrumentation, military infrared systems, and vehicle observable technology. Dr. Epstein is a fellow of the AIAA and the ASME and a member of the NRC's Board on Army Science and Technology (BAST).

Frank C. Gillette, Jr., received a B.S. in mechanical engineering from the University of Florida. Mr. Gillette retired from Pratt & Whitney in 1998, after 36 years of service, and now actively consults with Pratt & Whitney Large Military Engines, also performing reviews of Sikorsky helicopters and assessing damage tolerance of their aircraft. During his time at Pratt & Whitney, he played a major role in designing and developing almost every engine that powers the U.S. Air Force frontline fighter aircraft. As director of the F119 engine, he was responsible for the JAFE, YF-119, and F119 EMDPs. During these programs, he developed a thrust vectoring supercruise engine for the U.S. Air Force's new F-22 Raptor fighter. Mr. Gillette is currently a consultant for United Technologies and Belcan Corporation and participates in the final design reviews for the Belcan Corporation. He is active at the University of Florida and recently completed the search for dean of engineering and is on the Engineering Advisory Committee of the University of Florida Foundation board of directors. He is an active fellow in the ASME and an associate fellow of the AIAA. His expertise is in military systems acquisition, propulsion engineering, materials science and engineering, thermodynamics, aerodynamics, systems engineering, rocket propulsion engineering, and space science.

Brig Gen Wilfred Goodson retired from the Air Force in 1985 as the assistant chief of staff, studies, and analyses and commander of the Air Force Center for Studies and Analyses, Air Force Headquarters, Washington, D.C. He received a B.S. degree in basic sciences and engineering sciences and was commissioned a second lieutenant following graduation from the Air Force Academy in 1960. An Olmstead scholar, he began his study at the Defense Language School, Washington, D.C., in February 1964, and in September 1964 moved to Germany and entered the University of Heidelberg, where he received his doctorate in theoretical astrophysics in 1966. He graduated from the National War College in 1975. He is a senior pilot with 2,500 flying hours. His military decorations and awards include the Legion of Merit, Distinguished Flying Cross, Bronze Star Medal, Meritorious Service Medal with oak leaf cluster, Air Medal with six oak leaf clusters, Air Force Commendation Medal, and Republic of Vietnam Gallantry Cross with palm.

Jeffrey W. Hamstra graduated from the University of Michigan with an M.S. in aerospace engineering. Mr. Hamstra is currently a Lockheed Martin fellow in propulsion integration and is responsible for providing technical consultation and guidance, conducting program reviews, and ensuring technical integrity in the propulsion discipline across the entire Lockheed Martin aero enterprise. He has 20 years of experience in jet propulsion systems integration at Lockheed Martin Aeronautics Company and its Heritage organizations, including program experience from F-16, F-22, F-35 Joint Strike Fighter, and Skunk Works Advanced Development Programs. He has performed as an R&D principal investigator, aircraft project lead, and function department manager. He is familiar with U.S. aircraft engine industry, government propulsion organizations, and propulsion technology programs and has expertise in propulsion engineering, thermodynamics, aerodynamics, systems engineering, and aircraft propulsion. He was inducted as a Lockheed Martin fellow in 2003.

S. Michael Hudson retired as vice chairman of Rolls-Royce North America. After Allison Engine Company was acquired by Rolls-Royce, Mr. Hudson served as president, chief executive officer, chief operating officer, and a member of the board of directors of Allison Engine Company, Inc. During his tenure at Allison, he served as executive vice president for engineering, chief engineer for advanced technology engines, chief engineer for small production engines, supervisor of the design for Model 250 engines, chief of preliminary design, and chief project engineer in vehicular gas turbines. Mr. Hudson brings insight to propulsion engineering issues, related business issues, and the European perspective on aviation issues. He is currently a member of ASEB and served as chair of the NRC Committee on Technology Pathways: Assessing the Integrated Plan for a Next Generation Air Transportation System.

Clyde Kizer graduated from Eastern Michigan University in 1960 with a B.S. in biochemistry. After graduation, he enlisted in the aviation officer candidate course and became a naval aviator. During the following 15 years of active duty, Mr. Kizer participated in one astronaut recovery, flew three combat tours in Vietnam, graduated from the U.S. Naval Test Pilot School (USNTPS), served a tour as a USNTPS instructor, and flew as an experimental test pilot for 8 years. He left active duty in 1974 to join United Airlines but remained in the Naval Reserves for 8 more years. During that period, Mr. Kizer held a squadron command and retired from the Naval Reserves in 1982 with the rank of captain. He flew with United for 14 years as an engineering test captain and was promoted to director of engineering and then to vice president of engineering and was responsible for 1,100 personnel and all of the engineering and quality assurance activities for United. He left United in 1988 to join the Air Transport Association (ATA) as vice president, engineering and maintenance. At ATA Mr. Kizer assumed leadership of the Airworthiness Assurance Task Force. After that project was completed, in 1990, he left ATA to become the senior vice president of operations for Midway Airlines. In 1992, he joined Airbus Industries of North America as president of Airbus Service Company (later Airbus North America-Customer Services) and served in that position for over 12 years. In that capacity, he had total customer services responsibilities for all Airbus aircraft operating in North America, and spares and training responsibilities for all Airbus operators in the Western Hemisphere. Mr. Kizer's tenure with Airbus saw explosive growth for that company in North America. When he joined Airbus in 1992, there were 98 Airbus aircraft of all types in North America. When he retired from Airbus, in April 2004, there were 980 Airbus aircraft operating in North America.

Neil E. Paton (NAE) graduated from the Massachusetts Institute of Technology with a Ph.D. in materials science. Currently, he is the chief technology advisor and chairman of the Technology Advisory Board at Liquidmetal Technologies, where he has worked since March 2002. Prior to joining Liquidmetal, he served for 12 years as vice president of technology for Howmet Corporation and as president of Howmet Research Corporation, which developed products, processes, and materials for gas turbines. He also worked in materials development and advanced engineering for 20 years at Rockwell International, where he was involved in numerous programs, including the space shuttle program and the National Aerospace Plane program. He has experience in propulsion engineering, materials science and engineering, rocket propulsion engineering, aircraft propulsion and rocket/missile propulsion.

Jonathan Protz is currently an assistant professor of mechanical engineering and materials science at Duke University. Previously, he worked as a defense policy fellow through the Science and Technology Policy Fellows program of the American Association for the Advancement of Science (AAAS); as a strategy consultant for an international strategy consulting firm; and as a summer researcher at NASA and USAF civilian research centers. Dr. Protz's research interests include propulsion and power generation at the micro scale; dynamics and control of microsystems; and financial valuation, modeling, and analysis of engineered systems in aerospace and defense. Dr. Protz holds a Ph.D. from the Massachusetts Institute of Technology.

Rene G. Rendon is on the faculty of the Naval Postgraduate School, where he teaches acquisition and contract management courses in the M.B.A. and M.S. programs. In addition to teaching at the Naval Postgraduate School, Dr. Rendon has conducted research for the Office of the Under Secretary of

Defense (Acquisition, Technology, and Logistics) and the U.S. Navy and has taught acquisition management courses to foreign military officers and civilian officials. Prior to his appointment at the Naval Postgraduate School, he served for more than 22 years as an acquisition and contracting officer in the Air Force, retiring at the rank of lieutenant colonel. His Air Force career included assignments as a warranted contracting officer for the Peacekeeper intercontinental ballistic missile and the F-22 programs, a contracting squadron commander for an Air Force pilot training base, and the director of contracting for the Air Force's space surveillance satellite and space launch rocket programs. Dr. Rendon has earned bachelor's, master's, and doctoral degrees in business administration and has taught contract management courses for the UCLA government contracts program. He was also a senior faculty member for the Keller Graduate School of Management, where he taught M.B.A. courses in project management and contract management. He is also a graduate of the U.S. Air Force Squadron Officer School, the Air Command and Staff College, the Air War College, and the Department of Defense Systems Management College. Dr. Rendon is a certified professional contracts manager with the National Contract Management Association (NCMA), a certified purchasing manager with the Institute for Supply Management (ISM), and a certified project management professional with the Project Management Institute. He has received the prestigious Fellow Award from NCMA and was recognized with the Air Force Outstanding Officer in Contracting Award. Dr. Rendon is a member of the ISM Certification Committee and is on the editorial review board for the ISM *Inside Supply Management* magazine. He is a member of the NCMA board of advisors, as well as associate editor for its *Journal of Contract Management*. Dr. Rendon is coauthor of *Contract Management Organizational Assessment Tools* and has also published articles in *Contract Management* magazine, the *Journal of Contract Management*, *Program Manager* magazine, the *Project Management Journal*, and *PM Network* magazine.

Eli Reshotko (NAE) graduated from the California Institute of Technology with a Ph.D. in aeronautics and physics. Dr. Reshotko is currently the Kent H. Smith Professor Emeritus of Engineering at Case Western Reserve University. He was elected to the NAE in 1984 and is a fellow of the following societies: AIAA, ASME, the American Physical Society, and the American Academy of Mechanics, which he served as president. He is coauthor of over 100 publications and is affiliated with many task forces, committees, and governing boards, several of which he served as chair. His area of expertise is viscous effects in external and internal aerodynamics; two- and three-dimensional compressible boundary layers and heat transfer; stability and transition of viscous flows, both incompressible and compressible; and low-drag technology for aircraft and underwater vehicles. He has expertise in propulsion engineering, thermodynamics, aerodynamics, and aircraft propulsion.

Raymond Valeika retired from Delta as senior vice president-technical operations (TechOps). He directed a worldwide maintenance and engineering staff of more than 10,000 professionals, maintaining a fleet of nearly 600 aircraft. Currently, he is an independent consultant advising major companies on aviation matters and an internationally recognized senior airline operations executive with over 40 years of managing the maintenance operations of large airlines. Through his leadership and focus on continuous improvement of the human processes in aviation maintenance, Delta TechOps consistently rated at the top of the industry for performance benchmarks in the areas of safety, quality, productivity, and reliability. Mr. Valeika was honored with ATA's Nuts & Bolts award, recognizing his leadership in the aviation industry. Finally, his leadership of the human side has been recognized over the years with a Humanitarian Award from the Community Mayors of New York, New Jersey, and Connecticut, and Laurel from *Aviation Week and Space Technology* for his role with human factors training at Continental.

In October 1999, Mr. Valeika received the Marvin Whitlock Award from the Society of Automotive Engineers. Most recently, the Aviation Week Group honored him with a lifetime achievement award. He is currently a member of NRC's ASEB. Previously, he held senior executive positions with Pan Am and Continental Airlines as well as Delta. He graduated from St. Louis University with a degree in aeronautical engineering in 1964.

Alan van Weele is currently senior platform technical advisor with responsibility for employing Northrop Grumman's extensive experience on the Boeing 707 developed during the Joint STARS program into other similar military platforms based on the B-707 aircraft. He began his career in the Air Force, where he was assigned to the 1607th Air Transport Wing and became an airframe and engine technician. During his tenure at Dover Air Force Base he enrolled in the pre-engineering course offered by the University of Delaware. Upon discharge from the Air Force in 1960, he completed his engineering degree at Hofstra University, where he acquired a B.S. in engineering science. Mr. van Weele joined the Grumman Corporation in June 1965, where he was employed as a structural test engineer. This assignment involved him in all aspects of material, systems, structural, and fatigue testing of the Grumman products manufactured during that era. After that, he held a number of engineering and program management positions with increasing responsibility. In March 1978, Mr. van Weele was assigned to the hydrofoil program of the Israeli navy as the test and certification manager. Upon transition to Israel of the program in July 1982, Mr. van Weele assumed the additional responsibility of in-country program manager. In January 1985 he was appointed section head of the engineering test department, a position which he held until May 1986, when he was named director of vehicle engineering for the JSTARS program. During that assignment, he was responsible for all vehicle engineering aspects that transitioned the commercial Boeing 707 airliner into a military surveillance platform. In 1991, he assumed the additional responsibilities of follow-on full-scale development engineering manager responsible for producing the engineering design for the third test aircraft. This design package formed the bridge to the current production JSTARS aircraft. During formation of the JSTARS production program in early 1992, Mr. van Weele was assigned the task of activating the JSTARS production facility in Lake Charles, Louisiana, where he was named site manager and director of operations. In 1997, Mr. van Weele was reassigned to work with British Aerospace in the United Kingdom on a cooperative program that leveraged JSTARS technology into a business jet class of aircraft.

Francis Veldman is currently senior program manager, refueling systems modernization and sustainment, at Boeing. His responsibilities include leading an organization of 177 people composed of program managers, engineers, and functional support for KC-135, KDC-10, E-6, and MC-130 aircraft, with responsibility for modification and fleet support while developing organizational strategic goals and vision during site transition and realignment. Mr. Veldman is an Air Force command pilot with over 2,500 flying hours in C/KC-135, C-18, and Boeing-707 aircrafts. He graduated from the U.S. Air Force Academy with a B.S. in electrical engineering and from Western New England College with an M.S. in engineering management.

Obaid Younossi is a senior management systems analyst currently involved in analyzing cost and acquisition issues for the Department of Defense, the Department of the Navy, and the Department of the Air Force. Before joining RAND in 1998, Dr. Younossi was a member of the Navy's acquisition community, where he worked on the Joint Strike Fighter program, the F/A-18 E/F, and the AIM-9X missile. Since joining RAND, his research has focused on weapon system acquisition, cost analysis, and defense industrial base issues. He has led studies that investigated the reasons for cost growth in F/A-22 aircraft and the issues surrounding the restart of the C-2 aircraft and shutdown of the E-2C production lines, and he assessed various deterministic and probabilistic methods of cost risk estimations. He has advised the Investment Panel of the Defense Science Board. Dr. Younossi holds a B.S. in mechanical engineering from the University of Pittsburgh, an M.A. from George Mason University, and an M.P.P. (Master of Philosophy in Public Policy) and a Ph.D. in public policy from the George Washington University.

Appendix B

Meetings and Speakers

MEETING 1
APRIL 25-27, 2006
FAIRBORN, OHIO

Background and Sponsor Expectations
Rick Keefer, Program Manager
Propulsion Systems Squadron (PRSS/YN)

eLOG21
Dave Schwartz, Weapon Systems Sustainment Manager
Weapon Systems Sustainment Division (AF/A4MY)

Framework for Re-engining LCC Analysis
Mark Foringer
AF/A9RI

John Wallace, Cost Analyst
Air Force Cost Analysis Agency (AFCAA)

Kenneth McNeil, Lead Action Officer
AF/A9RI

Past Studies Overview/Results
Dave Edmunds
Propulsion Systems Squadron (PRSS/YN)

Large Aircraft Inventory
Mark Amos, Lead Engineer
Propulsion Systems Squadron (PRSS/YN)

KC-135 Re-engining
Gaddis Gann, Modification Support Squadron
327 TSG/GFT

C-5 Reliability Enhancement and Re-engining Program
Paul Sagasser, Chief, Flight Systems Engineer
C-5 Systems Group

Ed Norvaisis, Propulsion Integration Engineer
C-5 Systems Group

Airborne Warning and Control System (AWACS)/Joint Surveillance Target Attack Radar System (JSTARS) Re-engining
Sam Kimbrel, AWACS
A2SG/XRP

James MacStravic, JSTARS Deputy Program Director
E8SG/DC

Bruce Trask, JSTARS
E8SG/VA

B-52 Re-engining Study
Rafael Garcia, Deputy Director, 327 ACSG
327 BMSG/DC

448 EPSG Engine Life Management Plan Sustainment Metrics (TF33, JT8D, T56)
Otis Parker, TF33 Program Manager
448 Eagle Propulsion Sustainment Group

448 HPSG Engine Life Management Plan Sustainment Metrics (F101, F108, F118, TF39)
David Horn, Chief Engineer
448 Hawk Propulsion Sustainment Group

Fuel Saving Technology
Jeff Stricker, Chief Engineer
AFRL/PRT

B-1
Lee Gray
B1SG/ENE

C-17
Edward Kleinhans
PRSS/YC

C-130/C-130J
Capt Alex Sexton (via teleconference)
330 TASG/WSSCM

MEETING 2
MAY 23-25, 2006
WASHINGTON, D.C.

Quick-Look Study on Technology Options for Improved Air Vehicle Fuel Efficiency
Ann Karagozian, Chair, Air Force Scientific Advisory Board Task Force, and Vice Chair, Air Force Scientific Advisory Board

Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology
Obaid Younossi, Senior Analyst
The RAND Corporation

Air Force Depot Presentation
John Over, Director, 448 Combat Sustainment Wing
Tinker Air Force Base

Boeing Presentation
Lt Gen John Sams, Jr. (USAF, ret.), Vice President for Air Force Programs
The Boeing Company

Lockheed Martin Presentation
Jack O'Banion, Director, Air Mobility Requirements
Lockheed Martin Corporation

Northrop Grumman Presentation
Thomas J. Mackey, JSTARS Director for Support
Northrop Grumman Corporation

Michael O'Grady, JSTARS Re-engining Project Manager
Northrop Grumman Corporation

General Electric Presentation
Jim Shuppert, Director of Sales, Tanker/Transport/ISR Engines
GE-Aviation

Pratt & Whitney Presentation
Bennett Croswell, Vice President, Military Development Programs
Pratt & Whitney

Rolls-Royce North America Presentation
Lt Gen Steve Plummer (USAF, ret.), Senior Vice President for Defense Relations
Rolls-Royce North America

Ronald York, Vice President for Special Programs
Rolls-Royce North America

Norm Egbert, Vice President for Engineering and Technology
Rolls-Royce North America

Projected Supportability Costs
Mark Johnson, Deputy Director of Maintenance, Deputy Chief of Staff, Logistics, Installations and Mission Support, HQ USAF/A4MY

Re-engining Program Analysis Discussion
Lt Col Mark Foringer, Chief, Force and Infrastructure Assessment Division, HQ USAF/A9

MEETING 3
JUNE 13-15, 2006
ARLINGTON, VIRGINIA

Rolls-Royce Financing Presentation
Lt Gen Steve Plummer (USAF, ret.), Senior Vice President for Defense Relations
Rolls-Royce North America

Paul Freestone, Vice President and Customer Business Executive
Rolls-Royce North America

Alternative Fuels
William E. Harrison III, Director, National Aerospace Fuels Research Complex
Air Force Research Laboratory (AFRL/PRTG)

Southwest Airlines Conversation
Jim Sokul, Vice President Maintenance and Engineering
Southwest Airlines

General Electric Finance/Commercial Model Leasing Presentation
James Shuppert, Director of Sales
GE-Aviation

Gilbert Nockles, Senior Vice President
GE-Corporate Finance

Christopher Cantwell, Senior Vice President
GE-Capital Aviation Services

Patrick Cosgrove, Senior Vice President
GE-Capital Aviation Services

Winglets
Jay Inman, Vice President Programs
Aviation Partners Boeing

Fuel Supply and Pricing
Richard J. Connelly, Director
Defense Energy Support Center

Component Improvement Program
Don Hoying, U.S. Air Force Engine CIP Manager
Propulsion Systems Squadron (PRSS/YN)

Engine Model Derivative Program
Dave Irwin, Chief Engineer, Development Engines
Propulsion Systems Squadron (PRSS/YN)

Appendix C

Key Recommendations from Previous Studies

In its research for this report the committee looked at several studies of re-engining. Table C-1 lists the key studies, which are summarized in this appendix.

TABLE C-1 Previous Air Force Re-engining Studies

No.	Study Name	Prepared by	Date
1	Technology Options for Improved Air Vehicle Fuel Efficiency	Air Force Scientific Advisory Board	May 2006
2	B-52 Propulsion Capability Study	ACSSW/PRSS New Engines	November 2005
3	C-130 Enhanced Capabilities/Demonstration Programs	Snow Aviation International	October 10, 2005
4	AC-130U Alternate Engine Summary Report	Macaulay Brown/UTC	March 8, 2005
5	Task Force on B-52H Re-engining (Revised and Updated)	USD/ATL	2004
6	TF33 Re-engine Look-Ahead	Oklahoma City Air Logistics Center	June 2004
7	The Airforce KC-767 Tanker Lease Proposal: Key Issues for Congress	Congressional Research Service	2003
8	B-52 Re-engine Study Report	Boeing/Hannon Armstrong	September 30, 2003
9	B-1B Re-engining, Mission Flexibility (for Maj Gen Dan Leaf)	Boeing	July 29, 2002
10	KC-135 Engine Modernization Program: LCC Analysis	Boeing	March 9, 2000
11	TF33 Propulsion System Roadmapping Study	Pratt & Whitney	February 10, 1998
12	Findings of the B-52H Re-engining Cost IPT	SAF/FM	1997
13	Analysis of Aerial Tanker Re-engining Programs	Congressional Budget Office	September 1984

NOTE: ACSWW, Agile Combat Support Systems Wing; PRSS, Propulsion Systems Squadron; SAF/FM, Assistant Secretary of the Air Force (Financial Management and Comptroller); USD/ATL, Undersecretary of Defense Acquisition, Technology, and Logistics; UTC, United Technologies Corporation.

SUMMARY 1
TECHNOLOGY OPTIONS FOR IMPROVED AIR VEHICLE FUEL EFFICIENCY
AIR FORCE SCIENTIFIC ADVISORY BOARD
CHAIR: ANN KARAGOZIAN
MAY 2006

Scope

This study identifies potential near-, mid-, and far-term methods for improving air vehicle fuel efficiency in the Air Force. The study also determines relevant benefits of recent government propulsion efficiency programs and technologies (current and future) that could impact fuel efficiency.

Background

Between 2005 and 2025, the percentage of crude oil imported to the United States is estimated to grow from 63 to 70 percent of the total crude oil consumed. Within DoD, the Air Force is the largest consumer of fuel, with 58 percent, or 3.2 billion gallons, used in 2003. Of this, 81 percent was used for fueling aircraft. The largest percentage (54.2) of aircraft fuel is used by tankers and transport planes (FY98-FY04).

In the study, the cost of fuel is estimated by including the actual cost (Defense Energy Support Center (DESC) price to the Air Force) as well as the cost to transport the fuel via tanker. The cost to transport the fuel can be significantly higher than the actual fuel cost. Therefore it is necessary to account for this "fully burdened" cost of aviation fuel when comparing benefits of alternative solutions.

Findings

Fuel efficiency can be increased by making adjustments in three areas: aerodynamics (to increase lift to drag ratio), engine fuel consumption (to decrease thrust-specific fuel consumption (TSFC)), and weight (to reduce operational empty weight). It is estimated that large transport aircraft could realize as much as a 12 percent savings in fuel if there is a 10 percent increase in lift to drag ratio, a 13 percent savings for a 10 percent decrease in TSFC, and a 6 percent savings for a 10 percent decrease in operating empty weight (OEW). This information was calculated for an aircraft at Mach 0.8 at an altitude of 36,000 ft.

Over the past 50 years or so, the TSFC of engines has tended to decrease over time, starting with turbojet engines in the 1950s and ending with second-generation, high-bypass turbofans in the early 2000s. The potential for further gains in TSFC is projected to decrease in the next 15 years. However, tankers and transport aircraft tend to have a higher lift to drag ratio and lower TSFC than fighter aircraft, making them better candidates for TSFC improvement.

Current Programs

Current Air Force turbine engine development programs (IHPTET and VAATE) plan to improve engine performance over the next 10 years. These programs generally emphasize goals for military performance, not mobility. NASA aeronautics development programs are focusing on emissions, noise reduction, and engine control as well as ultraefficient engine technology (UEET). UEET has achieved a

15 percent reduction in carbon dioxide emissions for subsonic transports. Any focus on NO_x reduction can work against fuel efficiency.

Recommendations

The study offers near-, mid-, and far-term recommendations as well as a way to measure the benefit/cost ratios in five areas: engines, aerodynamics, structures and materials, operations, and alternative fuels.

SUMMARY 2
B-52 PROPULSION CAPABILITY STUDY

MARK AMOS, MIKE BURKE, PERRY SHELLABERGER,
AND LT COL GREG WEYDERT
AGILE COMBAT SUPPORT SYSTEMS WING (ACSSW)
PROPULSION SYSTEMS SQUADRON (PRSS)
NEW ENGINES
NOVEMBER 2005

Introduction

The B-52 is to remain in service through 2045. In 2005, the fleet included 76 B-52 aircraft with a total of 608 TF33-PW-103 engines as well as engine spares. Sustaining these TF33 engines is expected to become increasingly difficult as time goes by. Any B-52 re-engining solution must maintain the necessary aircraft capabilities and be able to accommodate future equipment modifications. Changes in the B-52 platform could include changes to the initial operational capability (IOC) of the standoff jammer, expected between 2012 and 2014, and to the next-generation, long-range-strike capability, as well as changes in mission needs. Re-engining in the 2012-2014 time frame would allow for the utilization of full engine life before the B-52 system is retired.

Relevant Previous Studies

1997, GAO B-52 cost effectiveness study
1998, LPJ study (TF33 Propulsion Roadmap)
1998, Pratt & Whitney study (TF33 Propulsion System Roadmap)
1998, Boeing re-engining study
2002, Defense Science Board re-engining study
2002, update to LPJ 1998 study
2004, update to DSB re-engining study

Proposed Study Scope

It was proposed that a study be undertaken that focuses on increasing the capability of the B-52 through re-engining while minimizing air vehicle impact and development risk. The study would concentrate on re-engining options that maintain the current B-52 aircraft/engine pylons and nacelles as well as TF33 takeoff thrust capability. It was also proposed that three re-engining options be explored: a complete TF33 core upgrade, a TF33/F119 hybrid upgrade, and a complete upgrade using military derivative engines (F119, F110, etc.). The estimated cost of this study was $125,000 depending on the approved final scope of the study. The results of a preliminary study could define the next step, perhaps requests for information (RFIs) and concepts for evaluation of the industry.

Proposed Study Figures of Merit

Ideally, any re-engining solution would provide a 10 percent improvement in TSFC, an average time on wing (ATOW) between 3,500 and 4,000 hours, and a 1 MW increase in power capacity. The re-engining program would also facilitate improvements in operating altitude, loiter, range, weapon/load delivery, hot-day takeoff, reliability, and maintainability of the B-52.

SUMMARY 3 (DRAFT)
C-130 ENHANCED CAPABILITIES DEMONSTRATION PROGRAMS
BRIEFING TO C-130 TCG WORLDWIDE REVIEW
SNOW AVIATION INTERNATIONAL (SAI)
MARIETTA, GEORGIA
OCTOBER 10, 2005

Scope

This study summarizes demonstrations of the tip tank (complete in September 2004), the unmanned aircraft system (UAS) AirLaunch (complete in April 2005), the short takeoff and landing (STOL) Herk (ongoing, July 2005 through October 2006), and the PW150 re-engining (pending) on the C-130 aircraft.

Tip Tank Demonstration

Tip tanks decreased the stall speed of the C-130 without increasing overall drag. The demonstration established the flutter-safe envelope, the structural response (during taxi and in flight), and the new C-130 flying characteristics. A summary of the aircraft stall and lift coefficient performance and the resulting inferred performance improvements are included.

UAS AirLaunch Demonstration

Pictures are provided of the UAS airborne and after release from the aircraft.

STOL Herk Demonstration

The STOL Herk program objectives include demonstrating the feasibility of the hybrid propulsion system and measuring the performance increases attributable to the installation of NP2000 propellers and the addition of two Pratt & Whitney 306C turbofans to a C-130E with T56-7A/B engines. The STOL Herk test bed provides a location to measure pressure flows on new C-130 nacelles; to create aerodynamic modifications for safe operation at lower airspeeds (and with critical engine failure); and to rewire and modernize key electrical system components.

The NP2000 propeller is described in detail, along with the existing STOL Herk avionics, nacelles, and aerodynamic modifications. The NP2000 propeller provides more thrust and more wing lift through aspiration than the 54H60 propeller. NP2000's better aspiration of the wing enables C-130 aircraft to fly 12 knots slower than the original stall speeds. Aerodynamic devices assure roll and yaw control during slow flight, in engine-out situations, and during takeoff (without power cutbacks). A C-130 with an extended chord and aileron provides more aileron effectiveness than a standard C-130 to mitigate engine failure. An extended chord, rudder, and dorsal area counter the greater thrust asymmetry created by outboard engine failure at slow speed and heavy weight; NP2000 software reduces the thrust decay of a failing engine, giving the pilot more time to respond. Finally, rudder effectiveness is increased via strakes and dorsals.

Conclusions

The high-flight-time ex-Southern Air Command transport L-100 has flown 90,000 hours, which confirms the attainability of C-130 life extensions and the airworthiness of the basic design. The SAI C-130 modern technology insertion demos and their sponsorship by DoD show a strong shared commitment to keeping legacy C-130 fleets viable and operationally effective for decades to come.

SUMMARY 4
AC-130U ALTERNATE ENGINE SUMMARY REPORT
MACAULAY BROWN/UNITED TECHNOLOGIES CORPORATION
MARCH 8, 2005

NOT FOR PUBLIC RELEASE

SUMMARY 5
TASK FORCE ON B-52H RE-ENGINING (REVISED AND UPDATED)
OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR ACQUISITION,
TECHNOLOGY, AND LOGISTICS
DEFENSE SCIENCE BOARD
WASHINGTON, D.C.
2004

Study Scope

The task force was asked to review and advise on key aspects of the policy and technology issues associated with re-engining the Air Force's B-52 fleet. Specifically, the task force examined relevant aspects of B-52 re-engining, including its impact on B-52 capability and demand for tanker support; fuel consumption; reliability, supportability, and availability; technical risks of re-engining; and financing options, including the use of Energy Savings Performance Contracting (ESPC).

Conclusions

1. The B-52H is the most versatile and cost-effective bomber in the inventory and re-engining makes it even more so.
2. The B-52H has the highest mission-capable rate of any of the three bombers, and is the only Conventional Air Launched Cruise Missile (CALCM) capable platform in the inventory.

3. That further significant reductions in the B-52H fleet are unlikely for the foreseeable future because:

   - The total assigned inventory (TAI) bomber fleet being reduced from 130 to 96, a deminimis number
   - There is no bomber aircraft currently in development
   - The B-52H is highly capability of accomplishing its assigned missions
   - The B-52H is flexible and able to adapt to future missions
   - The USAF chose to retire more than twice as many B-1 airframes as B-52H airframes
   - USAF has stated its intention to retain the B-52H through 2037

4. B-52H re-engining program represents low risk in the areas of program management, systems engineering, and affordability based on a re-assessment of the factors considered in the 1996 IPT evaluation.
5. B-52H re-engining is an attractive opportunity for the following financial and operational reasons:

   - Greater operational flexibility
   - Greater range
   - Reduced fuel burn
   - Reduced tanker demand
   - Depot savings through elimination of off-airframe engine maintenance
   - Field maintenance manpower savings

6. B-52H re-engining would serve as a good pilot program for expanding the ESPC Program in practice beyond facilities, and into mobility systems.
7. The task force concludes the economic and operational benefits far outweigh the program cost.

Recommendations

The task force recommends that the following actions should be taken to produce a promptly executable B-52 re-engining program, recalibrate the expected lifetime of the airframe, and quantify the logistics assets that could be redeployed to satisfy shortfalls elsewhere:

1. The Air Force proceed with B-52H re-engining without delay and place the program on a fast acquisition track in order to maximize the benefits and take advantage of the current business climate.
2. The Air Force proceed with a dedicated study to determine the optimum program, considering all the possible engines, service arrangements and financing options.
3. OSD commission a new independent long-term tanker requirements study that extends beyond FY05, based on new planning guidance, which includes the ability to conduct sensitivity analyses of B-52H re-engining as well as other planned and potential new receiver aircraft that will be in service over the expected lifetime of the tanker force, such as JSF.
4. The SPO and Boeing investigate the impact of eliminating low-level missions on projections of future airframe economic lifetime.
5. OSD and the Air Force investigate whether authority exists to use an Energy Savings Performance Contract or if legislative clarification is needed; and confirm the economic viability of Energy Savings Performance Contracting as a financing mechanism for B-52H re-engining.

6. OSD investigate the use of more robust analytical tools that allow the value of improved operational capabilities to be included in cost-benefit analyses used to support programmatic decision making.

Better analytical tools that quantify the logistics demands resulting from the deployment, employment, and sustainment of platforms will enable more informed force structure decisions and result in greater operational capability and flexibility for DoD's Total Obligation Authority.

SUMMARY 6
TF33 RE-ENGINE LOOK-AHEAD
OKLAHOMA CITY AIR LOGISTICS CENTER
TEAM TINKER
JUNE 2004

Background

Re-engining the TF33 fleet has been heavily evaluated in depth. Several re-engining studies have been undertaken since 1996. These studies include but are not limited to:

1. 1996, Boeing re-engining proposal
2. 1998, Director Martha Evans (SAF/AQI) initiated TF33 roadmap study
3. 2002, Propulsion Development Systems Office's Advanced Division (ASC/LPJ) tasked to update 1998 SAF/AQI study
4. 2003, JSTARS re-engining requesting funds
5. 2003, B-52H re-engining requesting approval

Study Focus

Lt Gen Wetekam, AF/IL, has requested a look-ahead at the feasibility of a fleetwide re-engining of the TF33. The look-ahead evaluation focuses on the pros and cons of each study.

Summary of the Benefits (Pros)

Studies have shown that re-engining can increase the reliability of an aircraft by up to 10 percent while increasing fuel efficiency between 19 and 29 percent. This leads to increased mission capability (increased mission capable) rates and mission altitude, decreased time to climb and required tanker support). Re-engining the fleet can also lead to environmental improvements such as reduced noise and emissions. Finally, the TF33 is capable of meeting its mission through the lifetime of all aircraft in the studies.

Summary of Detriments (Cons)

The economic payback of a TF33 re-engining investment can be as long as 20 to 30 years, and the cost savings are based on a reduced tanker fleet. In turn, the workload (manpower) loss must be offset; this may entail significant reductions in force (112 MAE/43 LPA) and have significant consequences for active duty, reserves, and guard personnel. Potential workload and manpower losses from FY04 to FY24 are summarized in a chart.

Conclusions

Re-engining the TF33 allows for many mission improvements. However, the cost of the program does not justify it. Repeated studies have reached this same conclusion. Any full-scale evaluation of the TF33 would require assistance from the Aeronautical Systems Center.

SUMMARY 7
THE AIR FORCE KC-767 TANKER LEASE PROPOSAL: KEY ISSUES FOR CONGRESS
CONGRESSIONAL RESEARCH SERVICE (CRS)
THE LIBRARY OF CONGRESS
WASHINGTON, D.C.
2003

Introduction

The Air Force wished to replace its KC-135E aircraft by leasing 100 new Boeing KC-767 tankers. It indicated that leasing was preferred because it would result in faster deliveries than outright purchase. Air Force leaders argued that a lease would allow it to husband scarce procurement dollars by making a small down payment. Although Congress authorized the proposed lease in the FY02 DoD Appropriations Act, it stipulated that the defense oversight committees must approve the lease. However, the Senate Armed Services Committee had not yet done so. The lease proposal was controversial, and a number of issues have been raised so far.

Is There an Urgent Need to Replace the KC-135 Fleet?

The Air Force stated that replacing the KC-135 was urgent, citing high costs, aircraft vulnerability to catastrophic problems, and the imminent closing of the 767 production line. Opponents of the lease stated that operating costs were controllable and would be far lower than the overall costs of leasing the 767; that the vulnerability was no more than that depicted in a 2-year-old study, which the Air Force had found acceptable; and that the 767 production line was viable until 2006-2008.

Is the KC-767 the Best Aircraft to Replace the KC-135?

If acquired, the KC-767 might be in DoD's inventory for 50 years. The Air Force said the KC-767 was much more capable than the KC-135. Opponents contended other aircraft were even better than the KC-767 in meeting the Air Force's requirements. The Air Force opposed re-engining KC-135Es, but opponents believed the idea merited attention, as did outsourcing aerial refueling.

Is the Air Force Cost Comparison Authoritative?

The Air Force's report to Congress calculated that a 767 lease would cost $150 million more than a purchase on a net present value (NPV) basis. This calculation, however, was sensitive to many assumptions. The CRS analysis showed that several assumptions built into its calculation would, if treated different from how they were treated in the Air Force report, change the calculation by hundreds of millions of dollars each. Although some assumptions could change the calculation to favor either the lease or the purchase, others—such as the discount rate used to calculate NPV and whether to use multiyear procurement for the purchase option—could be more likely to tip the comparison in favor of the purchase option.

Does This Issue Have Implications for Congressional Budget Oversight?

The proposed lease appeared to be an unprecedented method of funding major new defense procurements. Critics pointed out that this approach was coupled with exemptions from longstanding laws on budgeting and defense procurement. The proposed lease raised policy questions about the visibility of full costs for DoD programs in the congressional oversight process, including questions about locking in budgetary resources when costs are uncertain, appropriateness of using an operating lease for the proposal, the impact of a Special Purpose Entity, and the potential for deviation from full funding of the government's contractual liability.

Figures and Tables

This report also contains many figures and tables of interest.

Figures

Tables

SUMMARY 8
B-52 RE-ENGINE STUDY REPORT
BOEING/HANNON ARMSTRONG
SEPTEMBER 30, 2003

NOT FOR PUBLIC RELEASE

SUMMARY 9
B-1B RE-ENGINING MISSION FLEXIBILITY (FOR MAJ GEN DAN LEAF)
BOEING
JULY 29, 2002

Maj Gen Dan Leaf asked Boeing to find the best solution to increase B-1B mission flexibility, specifically with increased altitude capability. Boeing studied many aircraft modifications and subsystem upgrades and concluded that F119 re-engining was the best solution. The conclusion of the study was that the original B-1A altitude and Mach 2.2 speed (which the B-1B structurally inherited) could be restored with the increased specific thrust of the production F119 engine.

SUMMARY 10
KC-135 ENGINE MODERNIZATION PROGRAM: LCC ANALYSIS
BOEING
MARCH 9, 2000

Executive Summary

Oklahoma City Air Logistics Center (OC-ALC) completed a cost study in 1996 regarding the cost effectiveness of replacing the existing TF33-P102 engines with the CFM56 engine. The 1996 study concluded that the modification was not cost effective and indeed would cost the Air Force $974 million NPV more than its projected cost. The 40-year life cycle cost (LCC) in this study differed from the 1996 study by over $2 billion (NPV) and showed re-engining with the CFM56 to be the most cost-effective solution. Re-engining the remaining KC-135Es would have saved the Air Force approximately $3 billion in FY99 and approximately $7 billion then year (TY).

Methodology

The 1996 OC-ALC Excel LCC model was duplicated by copying the modeling parameters and manipulation techniques from the LCC spreadsheets furnished within the 1996 study (described in detail in Attachments D and E of original report.) However, the 1996 study was based on several key assumptions that time proved to be incorrect:

- Total engine removal (TER) rate of the TF33-W-P102 was assumed to be 0.55 removals per 1,000 engine flight hours. In fact, the TF33-W-P102 removal rate exceeded 0.55 every year since 1994 and has averaged over 0.70 since the 1996 study was completed.

- The TER rate was modeled in the 1996 study as steady state—that is, as never increasing over the next 40 years. Analysis of historical data reveals the TER rate has increased an average of 3.8 percent annually since 1985.
- Engine overhaul costs (EOCs) of the TF33-W-P102 were assumed to be $356,568. Actual overhaul costs have averaged $450,000 since the 1996 study was completed.
- EOCs in the 1996 study were also modeled as steady state and forecast not to increase over the next 40 years. Analysis of historical costs reveals that overhaul costs have actually increased over 6.7 percent annually since 1990 and 17.9 percent annually since the 1996 study was completed.

Changes in TERs and EOCs produced increases in engine support costs, which rose, on average, 13.2 percent annually since 1990 and over 18.5 percent annually since 1995. In this study, Boeing used the 1996 LCC study assumption, incorporated 3 additional years of actuarial engine support costs, applied a modest 4 percent annual engine support cost growth due to aging, and reduced the KC-135E conversion cost to $1.8 million.

Nonmonetary Benefits and Savings

This analysis focused on quantifiable engine support costs. However, the single tanker configuration led to additional nonmonetary benefits and savings:

- Logistics support infrastructure (reductions)
  —Parts and support equipment inventory reduction,
  —Technical order standardization,
  —Airframe depot maintenance streamlining,
  —Less crew training and fewer training materials,
  —Smaller logistics deployment footprint,
  —Large commercial population,
  —Part obsolescence concerns eliminated,
  —Commercial support options now viable,
  —Relieves TF33 depot floor space shortage,
  —Slower growth in engine support cost,
  —Commercial engine service bulletin and technical advisories,
  —Engine improvement costs shared with commercial sector, and
  —Fifteen known deficiencies in TF33 management plan eliminated.
- Operational benefits (improvements)
  —Greater fuel offload capability,
  —Greater loiter capability,
  —Shorter takeoff distance,
  —Increased engine reliability, fewer in-flight shutdowns,
  —Rotor burst containment inherent to design,
  —Meets Stage III (current) and Stage IV (future) noise requirements,
  —The usability of JP-8 in cold weather,
  —Increased operations from additional airfields, and
  —Less deployment planning needed.

SUMMARY 11
TF33 PROPULSION SYSTEM ROADMAPPING STUDY
PRATT & WHITNEY
FEBRUARY 10, 1998

NOT FOR PUBLIC RELEASE

SUMMARY 12
FINDINGS OF THE B-52H RE-ENGINING COST INTEGRATED PRODUCT TEAM (IPT)
ASSISTANT SECRETARY OF THE AIR FORCE FINANCIAL MANAGEMENT OFFICE
1997

Summary

The OC-ALC Financial Management division estimates the cost for re-engining the B-52H at $1.34 billion (including risk uncertainties), with a budget estimate (including only identifiable sources) at $2.128 billion. Two options for re-engining the B-52H are considered: a baseline purchase option and a leasing option. In the baseline purchase option, cost is analyzed by area as follows: depot (engines and aircraft), sustainable support (cost improvement programs and modifications), field level (personnel and material), fixed logistics (training and technical orders), aviation fuel, and time-critical technical orders (TCTOs). In the leasing option, costs are analyzed in the following areas: development and testing (FY97-FY01), products and installation (FY99-FY08), lease (FY01-FY36), Air Force program support (FY97-FY36), contractor logistics support (FY01-FY36), mixed fleet support (FY97-FY08), and, finally, aviation fuel.

Some cost areas are identified as high risk. These are areas where costs can be only poorly predicted—namely, TERs, depot cost per engine for two-level maintenance, modifications, TCTOs, and fuel inflation. Average and three-sigma values are assigned to these risk areas.

Using a risk-adjusted fuel index of 3.1, the leasing option will cost as much as or significantly more than maintaining the status quo over the next 30 years. Specifically, the total obligational authority for risk, lease, and buy is $8.608 billion, $9.922 billion, and $7.761 billion (FY97-FY37), respectively.

Using a risk-adjusted fuel index of 2.7, the leasing option will be significantly higher than the budget estimate in the next 30 years. The risk-adjusted cost baseline, lease adjusted for fuel uncertainty, and the budget baseline total obligational authority for FY97-FY37 is $8.608 billion, $9.560 billion, and $7.432 billion, respectively.

Conclusion

The range of risk in the cost estimation is $465 million to $2.878 billion. Switching to a leasing option adjusted for fuel cost risk instead of a risk-adjusted purchase option would cost $1.314 billion.

SUMMARY 13
ANALYSIS OF AERIAL TANKER RE-ENGINING PROGRAMS
CONGRESSIONAL BUDGET OFFICE (CBO)
SEPTEMBER 1984

As requested by the Subcommittee on Defense of the House Appropriations Committee, this paper discusses some of the issues associated with the re-engining of the KC-135 aircraft and illustrates the costs and effects of alternative approaches to re-engining. In accordance with CBO's mandate to provide objective analysis, no recommendations are made. In 1984, the Air Force had approximately 615 KC-135 aircraft, which accounted for the bulk of its tanker fleet. Two programs to replace the engines in these aircraft represented a multi-billion-dollar effort to maintain tanker viability. The first program, directed by the Air Force, replaced the J57 engines on KC-135As with new CFM56 engines (KC-135R). The second program, directed by Congress, salvaged and refurbished Pratt & Whitney JT-3D engines and related equipment from retired Boeing 707 aircraft to replace aging engines on the KC-135A (KC-135E).

Capability

According to official estimates by DoD, the fuel delivery capacity of the re-engined KC-135R would increase by an average of 50 percent over that of the existing KC-135A; fuel efficiency was expected to increase by 25 percent. The JT3D re-engining program was expected to increase fuel delivery capacity of the KC-135Es by an average of 20 percent over that of the KC-135A and fuel efficiency by about 12 percent. Both the KC-135E and the KC-135R required a shorter takeoff distance at maximum gross weight than the KC-135A, enabling tankers to land at additional airfields.

Cost

Without accounting for differences in capability, CFM56 re-engining was much more costly than JT3D re-engining. An undiscounted 20-year LLC (excluding research and development) was $57.9 million for the KC-135R and $46.7 million for the KC-135E. After applying DoD estimates of relative fuel delivery capacity (in KC-135A equivalents), the LLC per A equivalent (including acquisition) became very similar: $38.6 million for the KC-135R and $38.9 million for the KC-135E. These cost estimates were sensitive to fuel costs as well as tanker performance—which, in turn, depended on the range and type of tanker mission.

Availability of the Aircraft for Re-engining

Since the JT3D program involved salvaging and refurbishing existing commercial engines and other aircraft components, it was ultimately limited by the supply of donor Boeing 707 aircraft.

Aging

The desirability of investing in a re-engining program might have been influenced by the age of the KC-135 aircraft and the likely time required to complete the re-engining program. Also, if a new-generation tanker was needed to support a smaller but more advanced bomber force, it might have been important to consider cost-effective alternatives for tanker re-engining.

Support Requirements

Some concern was expressed by the Air Force about problems of logistics support for the JT3D engines.

Timing of Capability and Demand

Fluctuations in refueling demand as well as in demand to support general-purpose forces might have dictated the time frame during which re-engining was feasible.

Implications for the Guard and the Reserve

Congress focused the JT3D re-engining program on the KC-135s in the Air National Guard and the Air Force Reserve. The Guard and Reserve, however, did not maintain backup aircraft in their inventory. Thus, unless JT3D re-engining continued, there would have been no backup KC-135E aircraft.

Alternative Approaches for Tanker Re-engining

CBO examined three approaches for increasing the Air Force's tanker capability:

1. Continue the current CFM56 re-engining program at the maximum rate of six per month, for a total of 334 additional re-engined KC-135R aircraft.
2. Continue the CFM56 re-engining program at a reduced maximum rate of four per month, for a total of 334 re-engined KC-135R aircraft.
3. Combine the JT3D and CFM56 re-engining programs at a maximum rate of six per month, for a total of 334 additional re-engined aircraft—166 KC-135Es and 168 KC-135Rs.

Pros and Cons of Different Approaches

The combined JT3D/CFM56 approach offered more capability in the near to mid term (through 1992). Initially, this approach also cost significantly less ($4.3 billion over 4 years as opposed to $7.1 and $7.4 billion for the 6 and 4 per month CFM56 approaches, respectively). Also, having the CFM56 and JT3D programs ongoing could offer some competitive pressure to keep costs down. However, in the long run, the combined alternative would provide about 50 fewer KC-135A equivalents than either approach involving the pure CFM56. Also, the age of the JT3D engines and variability among them might have made them more difficult and costly to maintain.

The pure CFM56 re-engining approaches also offered advantages. The CFM56 was a brand-new engine, making it inherently more capable. Moreover, in the long run, the CFM56 might have cost no more than the combined JT3D/CFM56 approach. Air Force estimates of LLCs suggested that, over 20 years, the cost would have been about the same. Finally, the CFM56 was quiet and met the noise and emissions standards that applied to nonmilitary aircraft.

Appendix D

Background Information on Re-engining Requirements

The re-engining of an aircraft is a complex task and requires a substantial amount of predefinition work to be successful. The program starts with defining the missions the aircraft will undertake and the goals of the re-engining program—e.g., fuel saving, correcting performance shortfalls, taming the escalation of support costs, or a combination of these or other goals. In most cases the basic requirements can be derived from the initial design specification for the aircraft, modified by taking into account current requirements and then incorporating current Air Force policy directives for the program. The document input to industry by a DoD entity will form the core from which can be derived all the requirements for a re-engining program.

Once program requirements have been dissected and outlined, a contractor typically defines how it will undertake a re-engining program. Two basic elements in preparing a response to a Request for Proposals (RFP) are the development of a Technical Requirements Document (TRD) and a Work Breakdown Structure (WBS), so that costs and schedules can be developed for the program. A typical table of contents for a re-engining program is displayed below to provide some insight into the complexity and considerations that must be addressed to re-engine an aircraft.

TYPICAL WORK BREAKDOWN STRUCTURE FOR A RE-ENGINING PROGRAM INCORPORATED INTO A TABLE OF CONTENTS FOR A TECHNICAL REQUIREMENTS DOCUMENT

1. SCOPE
2. APPLICABLE DOCUMENTS
2.1 PROGRAM DOCUMENTS
2.2 MILITARY DOCUMENTS
2.3 CONTRACTOR DOCUMENTS
2.4 FEDERAL AVIATION ADMINISTRATION DOCUMENTS
2.5 OTHER DOCUMENTS
2.6 SOCIETY OF AUTOMOTIVE ENGINEERS, INC. (SAE) DOCUMENTS

2.7 RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA) DOCUMENTS
2.8 AEROSPACE INDUSTRIES ASSOCIATION OF AMERICA, INC. DOCUMENTS
2.9 REFERENCE DOCUMENTS
3. TECHNICAL REQUIREMENTS
3.1 PROPULSION SYSTEM DEFINITIONS
3.1.1 Propulsion Pod System Definition
3.1.1.1 Engine (FAR Part 33 Certified)
3.1.1.2 Nacelle
3.1.1.3 Engine Mounts
3.1.1.4 Engine BuildUp (EBU)
3.1.1.5 Pylon
3.1.2 Airframe Modifications
3.1.2.1 Cockpit Modifications
3.1.2.1.1 Auto Throttle Compatibility
3.1.2.2 Avionics Modifications
3.1.2.3 Wing Modifications
3.1.3 Definition of Terms and Abbreviations Used
3.2 PERFORMANCE
3.2.1 Design Life
3.2.2 Propulsion System General Criteria and Operating Envelope
3.2.3 Propulsion System Operation Characteristics
3.2.3.1 Takeoff Thrust
3.2.3.2 Maximum Continuous Thrust
3.2.3.3 Thrust-Specific Fuel Consumption
3.2.3.4 Warm-up Time
3.2.3.5 Engine Operating Time
3.2.3.6 Noise
3.2.3.7 Emissions
3.2.3.8 Infrared Emissions
3.2.3.9 Electrical Power
3.2.3.10 Engine-Driven Hydraulic Pump
3.2.3.11 Bleed Air
3.2.3.11.1 Engine-Generated Substances
3.2.3.11.2 Ozone
3.2.3.11.3 Pneumatic System Performance
3.2.3.11.3.1 ECS Bleed Air System (EBAS)
3.2.3.11.3.1.1 Bleed Air Pressure
3.2.3.11.3.1.2 Overpressure Control and Indication
3.2.3.11.3.1.3 Bleed Air Temperature
3.2.3.11.3.1.4 Overtemperature Control and Indication
3.2.3.11.3.1.5 Bleed Flow
3.2.3.11.3.1.6 Pressure Drop
3.2.3.11.3.1.7 Stability
3.2.3.11.3.2 Wing Thermal Anti-Ice (WTAI)
3.2.3.11.3.2.1 Bleed Air Pressure
3.2.3.11.3.2.2 Bleed Air Temperature

3.2.3.11.3.2.3 Bleed Flow

3.2.3.11.3.2.4 Temperature and Flow Exceptions

3.2.3.11.3.2.5 Low-Power Performance

3.2.3.11.3.2.6 Pressure Drop

3.2.3.12 Engine Overheat Prevention

3.2.3.13 Planned Maintenance Engineering Performance Envelope

3.3 STRUCTURAL REQUIREMENTS

3.3.1 Loads

3.3.1.1 General

3.3.1.2 Structural Design Loads

3.3.1.3 Factors of Safety

3.3.1.4 Material Strength Allowables

3.3.1.5 Repairability and Serviceability

3.3.2 Static Strength

3.3.3 Fatigue Criteria

3.3.3.1 Structural Fatigue Criteria

3.3.3.2 Acoustic Fatigue Criteria

3.3.3.3 Dynamics Criteria

3.3.3.4 Flutter Criteria

3.3.4 Slow Crack Growth

3.3.5 Containment

3.3.5.1 Engine Fan Blade Failure

3.3.5.2 Uncontrolled Rotating Machinery Failure

3.3.6 Bird Strike

3.3.7 Pneumatic Duct Rupture

3.3.7.1 Design for Duct Rupture and Ventilation

3.3.8 Weight and Center of Gravity

3.4 DESIGN AND CONSTRUCTION

3.4.1 General

3.4.2 Materials and Processes

3.4.2.1 Finishes

3.4.3 Physical Characteristics

3.4.3.1 Aerodynamic Smoothness Criteria

3.4.4 Identification Markings

3.4.5 Electromagnetic Interference (EMI), High-Intensity Radiated Field (HIRF), and Lightning Effects Protection

3.4.5.1 Electromagnetic Interference (EMI), High-Intensity Radiated Field (HIRF) Protection, and Lightning Indirect Effects Protection

3.4.5.2 Bonding, Shielding, Static Discharge and Lightning Direct Effects Protection

3.4.5.3 Lightning Protection Features

3.4.6 Interchangeability

3.5 MAJOR SYSTEM DESIGN REQUIREMENTS

3.5.1 General

3.5.2 Engine Mounting System

3.5.2.1 General

3.5.2.2 Mounting Structure

3.5.3 Nacelle

3.5.3.1 General

3.5.3.2 Inlet Cowl

3.5.3.2.1 Cowl Doors

3.5.3.2.1.1 Hold-Open Provisions

3.5.3.2.1.2 Pressure Relief Door

3.5.3.3 Primary Exhaust Nozzle (as applicable) and Plug

3.5.3.3.1 Nozzle Area

3.5.3.4 Cooling and Ventilation

3.5.3.4.1 Integrated Drive Generator (IDG) Cooler Air

3.5.4 Aft Cowl/Thrust Reverser

3.5.4.1 Aft Cowl (as Applicable)

3.5.4.2 Thrust Reverser Design Requirements

3.5.4.2.1 Thrust Reverser Effectiveness

3.5.4.2.2 Thrust Reverser/Aircraft Compatibility

3.5.4.2.3 Safety and Reliability

3.5.4.2.4 Thrust Reverser Safety

3.5.4.2.5 Safety Structural Integrity

3.5.4.2.6 Fail-Safe and Discrete Source Damage Requirement

3.5.4.2.7 Structural Capability

3.5.4.2.8 Emergency Landing

3.5.4.2.8.1 Rejected Takeoff

3.5.4.2.8.2 Inflight Inadvertent Deployment up to 350 KCAS[1]

3.5.4.2.8.3 Inflight Inadvertent Deployment Above 350 KCAS

3.5.4.2.8.4 Rejected Landing

3.5.4.2.8.5 Others

3.5.4.2.9 Reliability/Safety

3.5.4.2.10 Reverser Functional Requirements

3.5.4.2.11 Ground Maintenance Operation

3.5.4.2.12 Lock Sensors

3.5.4.2.13 Safety/Fail-safe Requirements

3.5.4.2.14 Safety Analysis

3.5.5 Pylon

3.5.6 Fire Protection

3.5.6.1 Fire Prevention

3.5.6.2 Fire Detection

3.5.6.2.1 Leak Detection

3.5.6.3 Fire Containment

3.5.6.4 Fire Extinguishing

3.5.7 Subsystems

3.5.7.1 Pneumatic System (including Anti-Icing)

3.5.7.1.1 General System Functional Requirements

3.5.7.1.1.1 System Design Requirements

3.5.7.1.1.1.1 Design

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[1] Knots calibrated airspeed.

3.5.7.1.1.1.2 Endurance
3.5.7.1.1.1.3 Vibration
3.5.7.1.1.1.4 Flow Resonance
3.5.7.1.1.1.5 Pressure Drop
3.5.7.1.1.1.6 Structural Integrity
3.5.7.1.1.1.6.1 Proof Pressure
3.5.7.1.1.1.6.2 Burst Pressure
3.5.7.1.1.1.6.3 Thermal Effects
3.5.7.1.1.2 Equipment Design Requirements
3.5.7.1.1.2.1 Maximum Flow
3.5.7.1.1.2.2 Bleed Port Location
3.5.7.1.1.2.3 Bleed Air Shutoff
3.5.7.1.1.2.4 Reverse Flow
3.5.7.1.1.2.5 Duct Routing
3.5.7.1.1.2.6 Duct Surface Temperatures
3.5.7.1.1.2.7 Foreign Material Ingestion
3.5.7.1.1.2.8 Thermal Compensation
3.5.7.1.1.2.9 Mounting
3.5.7.1.1.2.10 Tubing Bends
3.5.7.1.1.2.11 Brackets
3.5.7.1.1.2.12 Controls
3.5.7.1.1.2.13 Duct Connections
3.5.7.1.1.2.14 Tube Connections
3.5.7.1.1.2.15 Flow Direction
3.5.7.1.1.2.16 Safety Wire and Stakes
3.5.7.1.1.2.17 Leakage
3.5.7.1.1.2.18 Valves
3.5.7.1.1.2.18.1 Valve Position
3.5.7.1.1.2.18.2 Valve Position Indication
3.5.7.1.1.2.18.3 Check Valves
3.5.7.1.1.2.19 Condensation
3.5.7.1.1.2.20 Filters
3.5.7.1.1.2.21 Adjustment Covers
3.5.7.1.1.2.22 Mounting Provisions
3.5.7.1.1.2.23 Test Provisions
3.5.7.1.1.2.24 Checkout Provisions
3.5.7.1.1.2.25 Welding
3.5.7.1.2 Specific System Functional Requirements
3.5.7.1.2.1 ECS Bleed Air System (EBAS)
3.5.7.1.2.2 Engine Pneumatic Start System
3.5.7.1.2.3 Wing Thermal Anti-Ice System
3.5.7.1.2.4 Engine/Nacelle Anti-icing System
3.5.7.1.2.5 Aircraft Equipment Pressurization System
3.5.7.2 Bleed Air Leak Detection System
3.5.7.2.1 System Functional Requirements
3.5.7.2.2 Functional Interface Characteristics

3.5.7.3 Starting System
3.5.7.3.1 System Requirements
3.5.7.3.2 Functional Interface Characteristics
3.5.7.4 Hydraulic System
3.5.7.4.1 Lines and Fittings
3.5.7.4.2 Pumps
3.5.7.5 Electrical System
3.5.7.5.1 Interface Definition
3.5.7.5.1.1 Electrical Power System Interface
3.5.7.5.1.1.1 Generator Feeders
3.5.7.5.1.1.2 Engine Electrical Power
3.5.7.5.1.1.3 Generation System Signals
3.5.7.5.1.2 Electrical Signal Interface
3.5.7.5.1.3 Mechanical Drive Interface
3.5.7.5.1.4 Generator and Drive Cooling Interface
3.5.7.5.2 Performance Characteristics
3.5.7.5.2.1 AC Generating System
3.5.7.5.2.1.1 Integrated Drive Generator (IDG)
3.5.7.5.3 Electrical Connectors
3.5.7.5.4 Wiring
3.5.7.5.5 Grounding
3.5.7.5.6 Wiring Installations
3.5.7.5.6.1 Wire Routing
3.5.7.5.6.2 Electromagnetic Compatibility
3.5.7.5.7 System Interfaces
3.5.7.5.8 System Functional Requirements
3.5.7.5.9 Functional Interface Characteristics
3.5.7.6 Instrumentation
3.5.7.6.1 Engine Performance/Condition Functional Interface Characteristics
3.5.7.6.2 Engine Vibration Monitoring System (Provisions Only)
3.5.7.7 Ignition System-General
3.5.7.8 Fuel System
3.5.7.8.1 General
3.5.7.8.2 Fuels and Additives
3.5.7.8.3 Functional System Requirements
3.5.7.9 Propulsion Control System
3.5.7.9.1 Electronic Engine Control System (Option)
3.5.7.10 Engine Lubrication System
3.5.7.10.1 System Functional Requirements
3.5.7.10.2 Functional Interface Characteristics
3.6 RELIABILITY, MAINTAINABILITY, AND SAFETY
3.6.1 Reliability
3.6.2 Maintainability
3.6.3 Safety and Human Factors
3.6.3.1 Controls Separation
3.6.3.2 Hydraulic Isolation

3.6.3.3 Dry Bay
3.6.3.4 Fuel System Isolation
3.6.4 Integrated Logistics Support
3.6.4.1 Supply Support
3.6.4.2 Support Equipment (SE)
3.6.4.3 Logistics Support Analysis
3.6.4.4 Training
3.6.4.5 Turnaround Time (TAT)
3.6.4.6 Utilization Rate
3.6.4.7 Diminishing Manufacturing Sources and Material Shortages (DMSMS)
3.6.4.8 Availability
3.6.4.9 Scheduled Maintenance
3.6.5 Flight Simulator
4. OPERATIONAL SAFETY, SUITABILITY, AND EFFECTIVENESS (OSS&E)
5. PREPARATION AND DELIVERY
5.1.1.1 General
5.1.1.2 Preservation
5.1.1.3 Packing and Handling Loads
5.1.1.4 Deliverable Configuration
6. APPENDIX I—INTERFACE CONTROL DOCUMENTS
7. APPENDIX II—SCHEMATICS
8. APPENDIX III—FATIGUE SPECTRUM

Appendix E

Background Information on Lessons Learned from Previous Re-engining Programs

BACKGROUND

The air transport industry in the United States is capital intensive and has exceedingly low profit margins in comparison to traditional industries. In a recent year the airlines lost more money collectively than they had made cumulatively (and collectively) since their inception (see Figure E-1). The data in

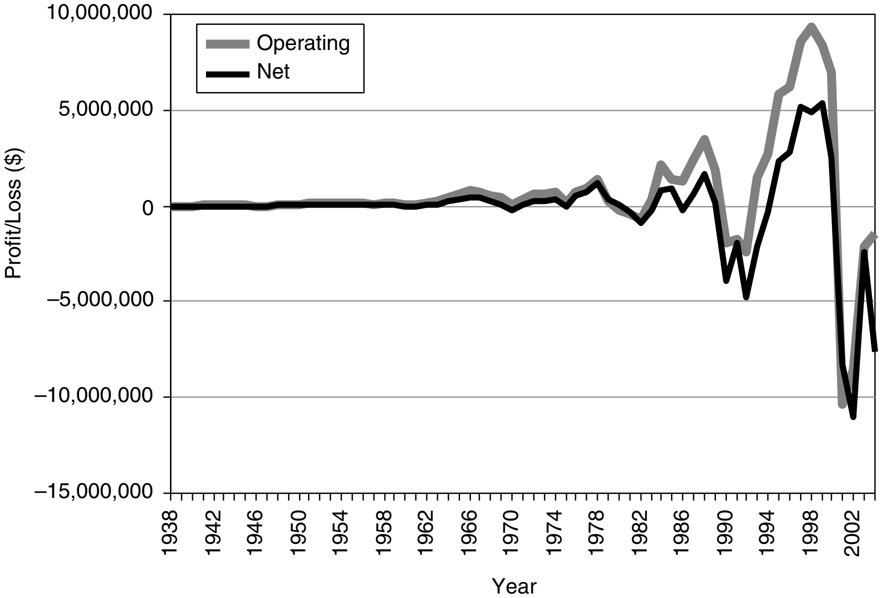

FIGURE E-1 Airline profit history. SOURCE: Airline Transport Association annual data.

Table 2-1 reflect the activity of U.S. passenger and cargo airlines as defined by the U.S. Department of Transportation under Chapter 411 of Title 49 of the U.S. Code.[1]

Throughout most of its history, the industry worked under economic and regulatory constraints intended to provide a safe and economically viable national transportation system for the traveling public. The industry experienced a degree of economic deregulation in 1978, the intent of which was to allow market forces to drive the industry to the appropriate size and economic viability. Since the industry has never been fully deregulated from an economic standpoint, the intent of that legislative action was never fully realized. Following deregulation, a number of airlines, including some of the best-known international airlines, sought economic protections under Chapter 11, merged with other air carriers, or went out of business under Chapter 7 provisions.

In the early years (1930s) of the formation of the air transport industry in the United States, aircraft and engines were experiencing exponential growth as a result of technology development. Airlines were established and went out of business with great frequency. The regulatory agency—the Civil Aviation Association—was in its early development and concentrated its efforts on establishing regulations for the certification of personnel and equipment to meet safety and standardization requirements. At that time no incentives existed for airlines to conduct re-engining or engine performance improvement studies because improved aircraft and engines were entering the marketplace continually.

In the 1940-1950 decade, the air transport industry flew aircraft developed before World War II, and since all aviation materials were committed to the war effort, little activity was dedicated to improving performance or re-engining, except for engine modifications required to maintain airworthiness.

In the next two decades, 1950-1970, the airline industry initially adapted aircraft and designs primarily developed for military applications. The last models of piston-powered aircraft stretched the limits of altitude, range, and power for the technology of the time. Individual airlines resisted, then embraced, turbojet-powered aircraft as a means to go farther, faster, and higher in order to gain their share of the transportation market. Once again, the development of structural, aerodynamic, power plant, and systems technologies regularly led to new airliners with better performance. Traditional thinking was to operate an aircraft type until a newer aircraft reached the market that provided significantly better cost or revenue generation or until the growth in maintenance cost dictated replacement (generally every 15-17 years or less). Once again, not much was known about re-engining, and engine modifications were undertaken predominately to maintain airworthiness standards.

During the 1970s and the first part of the 1980s, the airlines were in the midst of the feast-or-famine days of deregulation. For the first time ever, major air carriers were gathering the assets of other carriers as those carriers ceased to exist, in order to meet the capacity demand unleashed by relatively unrestrained growth. Significant efforts were devoted to aircraft and engine technology modifications to achieve standardization within the hodge-podge of airline fleets that was coming into being. Immediately prior to and during this period, aircraft were commonly "overbuilt" with respect to structure to overcome the limiting factors of design technology and tools and to meet the overriding requirement for long-term structural strength.

Engineering tools and technology combined during the later 1980s through 2000 to provide aircraft and engines that were optimally designed to meet the range and payload requirements of their intended use. Excess structure was eliminated, and new materials and techniques were employed to ensure that an aircraft would meet certification and service life expectations while having the lowest practical empty weight in order to reduce fuel consumption. Computer-aided design and manufacturing techniques al-

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[1] More information on Chapter 411 may be found at http://www.law.cornell.edu/uscode/uscode49/usc_sup_01_49_10_VII_20_A_30_ii_40_411.html. Last accessed on January 22, 2007.

lowed engineers to optimize aerodynamics and manufacturing techniques to minimize weight and drag. At the same time, aircraft and engine development and certification costs increased significantly. Not only because of economic constraints but also because these optimizations have for the most part already been carried out, there are unlikely to be future opportunities to improve fuel efficiency to justify re-engining a new generation of aircraft. Engine modifications will probably continue to be required for reasons of airworthiness, and it is possible that engine modifications or upgrades may provide an opportunity to maintain or improve performance and to realize fuel savings.

GENERAL FINDINGS

Analysis

The technical requirements to determine the cost/benefit of engine modification, upgrade, or re-engining are much the same for the commercial and military fleets. Basic engineering, maintenance, materials, and operational considerations are the drivers of such studies.

Airline experience includes relatively frequent modifications to existing engines in order to maintain airworthiness, to comply with environmental requirements (noise/emissions), to retain or improve performance (generally with respect to temperature), to reduce recurring maintenance costs, and to provide standardization and commonality between different engines within an airline's fleet. Although airlines generally handle their airframe and engine maintenance programs as totally independent activities, aircraft utilization of about 3,000 hours per year generally provides ample opportunity to modify engines.

Both the capital investment and the operational costs to accomplish engine maintenance are relatively high. For this reason, airlines that choose to do in-house engine maintenance generally plan for an uninterrupted flow of engines through their facilities. In addition, the Federal Aviation Administration (FAA) publishes engine-oriented airworthiness directives (ADs) when needed to address potential safety issues. These ADs stipulate maintenance and/or engineering action on the part of the airlines that must be accomplished in a timely manner. These operational and safety concerns frequently result in the recall of an engine for maintenance before its scheduled time. Such a proactive effort can result in a separation of the induction programs for airframe and engine maintenance. This allows the airlines to accomplish engine modifications, whether mandated or self-initiated, relatively quickly.

Airline technical organizations work with their internal finance organizations to develop a business plan for review of potential engine modification, upgrade, or re-engining. Generally, an original equipment manufacturer (OEM) or other outside entity is employed to assist in the verification/justification process. Developing a cost/benefit analysis involves determining the following parameters:

- The fully burdened cost of the various alternatives, including these:
    - —Engine kit costs
    - —Accessory costs
    - —Airframe modification costs
    - —Operating inventory costs
    - —Man-hour costs for program engineering and maintenance
    - —Certification costs
    - —Technical manual/documentation costs
    - —Maintenance costs related to inspections and shop visits
- The indirect costs of the engine alternatives, including these:

    - —Weight empty impact
    - —Out-of-service time costs
    - —Costs of training for flight crew, maintenance crew, and station crew
    - —Costs of training out-of-service personnel
- The service life remaining to verify financial return on investment, including these:
    - —Structural life verification
    - —Maintenance cost escalation
    - —Aircraft systems life/cost verification
- The benefits of various engine alternatives:
    - —Maintenance shop visit cost reduction
    - —Fuel consumption savings (trip cost impact)
    - —Performance improvement, where applicable, in takeoff distance, time to climb, cruise altitude, landing distance, range, payload, and reduced thrust opportunities

LESSONS LEARNED FROM COMMERCIAL RE-ENGINING PROGRAMS

Re-engining Experience

In recent history only one aircraft series, the DC-8-60 series, was re-engined by major airlines of the U.S. air transport industry. The experience of one passenger airline that conducted a conversion of JT3D-3 engines on a DC-8-61 aircraft to CFM56-2 engines reported that standard net present value (NPV) calculations of cost/benefit directly tied to the program were relatively accurate. The program met all of its expected financial and operational goals to the point that the trip costs for the newly re-engined DC-8-61 were the best of all the airline's fleets (six different types of aircraft) except for the 767 aircraft that was then in delivery to the airline. The DC-8/JT3 combination was an ideal candidate for re-engining because the DC-8 had significant structural reserves and the CFM56 turbofan engine had better efficiency and performance than the first-generation turbojet JT3D engine.

Unplanned Costs

Unplanned costs extraneous to the re-engine program resulted from the growth of costs for regulatory, marketing, and flight operations. Due to an increase in FAA ADs, aircraft downtime provided the opportunity to campaign the aircraft to complete the AD requirements in an accelerated manner rather than to suffer the detrimental effects of accumulated and nonproductive, repetitive access and inspection activities. In addition, completing the projects as quickly as possible averted a potential adverse psychological impact on safety and reliability.

Marketing took the opportunity to modify aircraft interiors in order to make them more attractive to airline passengers. It is seldom possible to verify cost/benefit analyses of such activities.

Flight operations took the advantage of aircraft downtime to standardize the various cockpit configurations that resulted from first-time-ever purchases of aircraft from other airlines. Although this project was not rigorously scrutinized from a cost/benefit standpoint, it made consummate sense from the standpoints of standardization and labor/management relationships.

These projects were not considered in developing the business case but became priorities that arose during the time between program justification and implementation. These costs were later justified independently and added to the overall program man-hours, materials, and operating inventory and out-of-service costs.

Operational Contribution to Unplanned Costs

The most dramatic unplanned impact on the re-engine program resulted from concurrent changes in air traffic control procedures that kept all airline aircraft at cruise speed and cruise altitude until they were close to major airports. This was done for reasons of fuel conservation and traffic volume. The re-engining program produced aircraft with less cruise drag and higher residual thrust at idle throttle, making it more difficult for the flight crews to slow down and get down. Since the DC-8 does not have brakes to control in-flight speed, the pilots used the flaps (at limit flap speeds) to create the drag needed to slow down before descending. This use of the flaps generated significant uncalculated and unplanned structural loads. In addition, the thrust area that impacted the flaps in the landing configuration had higher residual level and was greater than that of the JT3 engine. A “thrust gate” had been provided on the flaps to reduce the area of impact of the JT3 engine, but the core of the engine impinged on significant wing surface around the thrust gates and on CFM56 fan thrust patterns. As a result of these unplanned loads, one of the aircraft suffered a flap retention failure that almost resulted in the loss of a flap. Corrective action involved an emphasis on proper flap use during transition and recurrent flight crew training periods, much less time between flap inspections, and the replacement of damaged parts. These actions affected costs.

LESSONS LEARNED FROM MILITARY RE-ENGINING PROGRAMS

Similar to the passenger airline re-engining program that replaced JT3D-3 with CFM56-2 engines on DC-8-61 aircraft, the KC-135 re-engining program turned out to have accurately predicated performance improvement. However, the standard NPV costs and benefits calculated in the course of initial program justification could not be substantiated. Significant changes in quantities of aircraft and in the duration of the modification program reduced the benefits that had been projected by the initial cost/benefit analyses. That being said, and although force structure and operational utilization are not within the scope of this study, the data clearly indicate a dramatic increase in the mission utilization rate for KC-135 tanker aircraft with the new CFM56-2 (F108) engines. Re-engine programs involve much more than adding new engines on the wing.

Additional Capability

As part of the KC-135 re-engining program a new, heavier-duty main landing gear was added. This modification was not required because of the new engines, but was undertaken to exploit the increased thrust available and to allow the aircraft to completely fill their fuel tanks, which had not been possible for the power-limited KC-135 with J57 engines. There is often a natural inclination to take advantage of the analysis, test, and verification efforts of an existing modification program by adding new capability at the same time. This was and can be a cost-effective approach to increasing the capabilities of an aircraft, but the added costs and benefits of such modifications are not considered as part of a re-engining program.

Complexity of the Modification

There is a general lack of understanding of the magnitude and complexity of any re-engining program. A re-engining program affects just about every system on an aircraft (electrical, hydraulic, pneumatic, aerodynamic flight controls, avionics, and structural). In addition to the modifications to the aircraft itself, a significant effort to revise the technical manuals (performance, aircrew, maintenance, training, and repair), as well as support equipment, initial spares, maintenance concepts, and engineering substantiation analyses, is required. Engine accessories have to be changed, even if the selected engine is a commercial in-production aircraft, to meet military mission requirements. Even engines of the same thrust range will require significant analysis and certification effort, whether to FAA or military standards. Because a re-engining program impacts so many aircraft systems, obsolete and line replaceable units having a low mean time between failures are also replaced with newer alternatives and become part of the modification.

Program Schedule and Cost

For various reasons the Air Force failed to take advantage of favorable schedules or prices for acquisition and installation during the KC-135 re-engining program. Schedule extensions and annual purchases that were less than the best economic quantity increased total program costs. Multiple changes to production quantities and schedules further increased costs. These changes resulted in increased acquisition cost, a longer payback period, and fewer modified aircraft.

Future Re-engining Potential

Aircraft and their engines and weapons systems are designed in an integrated fashion to provide optimum performance and characteristics for planned missions. Unexpected costs and/or operational implications are likely to result from any change to the engines regardless of how much planning and analysis was committed to the development of the program. These risks can be mitigated by the involvement of all of the organizations affected by the program (engineering, maintenance, material, flight operations, technical publications, training, finance, etc.). This multiorganizational approach will help to prevent program surprises but is an impediment to rapid action in the face of high-priority economic, operational, or regulatory needs.

Commercial Re-engining

It is unlikely that next-generation commercial aircraft will lend themselves to potential re-engining campaigns in the near term, because the engines and airframes are highly optimized to meet service requirements, engine technology is not improving sufficiently or fast enough to justify significant expense, and structural and certification constraints pose a significant cost burden that will be difficult to bear.

Military Re-engining

Conceptually, re-engining large, nontactical military aircraft remains an attractive option for three reasons: (1) the low utilization rate leads to much longer service life for the weapons systems, (2) the probability of major advances in engine technology increases along with the service life of the weapons systems, and (3) mission suitability generally transcends financial considerations as the primary analysis criterion.

Appendix F

Background Information on Re-engining the C-130

This appendix contains some of the information and analysis used in preparing the section on re-engining the C-130 in Chapter 3 of this report.

ENGINE OPTIONS AND ECONOMICS

The acquisition and support options for retrofitting the engines and props on selected C-130 aircraft range from, on the one hand, conventional military competitive purchase of engineering services and hardware and maintenance and support using indigenous assets to, on the other hand, full operating lease arrangements in which equipment is contractor owned and supported. A review of current military practices for acquiring propulsion systems in this class of aircraft indicates that a hybrid approach may be most suitable for some of the re-engining options reviewed here. For example, the engines for the V-22 and C-130J aircraft are purchased in the normal way and the engines are supported on an operating-time basis, with a contractor supplying labor and service for parts (Freestone, 2006). This approach is representative of current commercial practices in the civil airline business and is now also favored by the military services.

Evaluating the impact of savings associated with such maintenance contracting approaches is beyond the scope of this review since a portion of the savings comes from reducing the government payroll and relief from inventory and logistic requirements. The economic evaluations shown here are therefore based on conventional hardware and engineering service procurement and fuel savings. In addition to straightforward hardware purchase arrangements it may be possible to negotiate trading in the existing T56 engines, which have residual value in the marketplace. Such an arrangement was used in past Army engine upgrade programs. Also, no attempt has been made to evaluate the possible effect of eliminating a portion of the fleet and staffing requirements, which can result from increased aircraft performance, in turn a consequence of the reduced fuel consumption and improved operational capability offered by a re-engined fleet.

The first-order financial component of retrofit development, hardware acquisition, and fuel savings is shown in Table F-1. Note that the engine cost data shown here were supplied by the contractors and have not been through any form of procurement verification.

A financial analysis using the information in Table F-1 and the cost assumptions shown in Table F-2 produce the cash flow trends shown in Figure F-1. The trends indicate that the most affordable option is an upgrade of the existing T56; the second most affordable is a retrofit with an existing derivative of the T56. The new AE 2100 is the least affordable based on the comparisons of maximum negative cash flow and payback time.

However a focus on fuel savings relative to re-engining investment (Table F-3) indicates that the new engine option provides the greatest fuel savings for an initial investment. The financial analysis shown here is extracted from a single study to provide consistency (Egbert and York, 2006). That study did not include the PW150, but it should be noted that this engine offers an attractive alternative to the AE 2100 in that the engine is of approximately the same power level and is somewhat less expensive

TABLE F-1 Components of Financial Evaluation[a]

Costs	T56/S3.5	T56/A427	AE 2100	PW150
Engine costs	0.433	0.753	1.0	0.965
Propeller costs (million $)	0.225	0.225	0.250	0.250
Nonrecurring costs of the re-engining (thousand $)	50	17	30	70
Nonrecurring costs of modifying the airframe (thousand $)	10	15	15	25[b]
Annual fuel savings (million gal)	8	13	28	27

[a] Engine costs for the AE 2100 were provided from an average of contractor-provided data; costs for the other engines were calculated using the percentages in Egbert and York (2006). They are expressed here as relative to avoid the use of proprietary data; other costs and the fuel savings are from Egbert and York (2006) or other contractor data.

[b] Committee estimate.

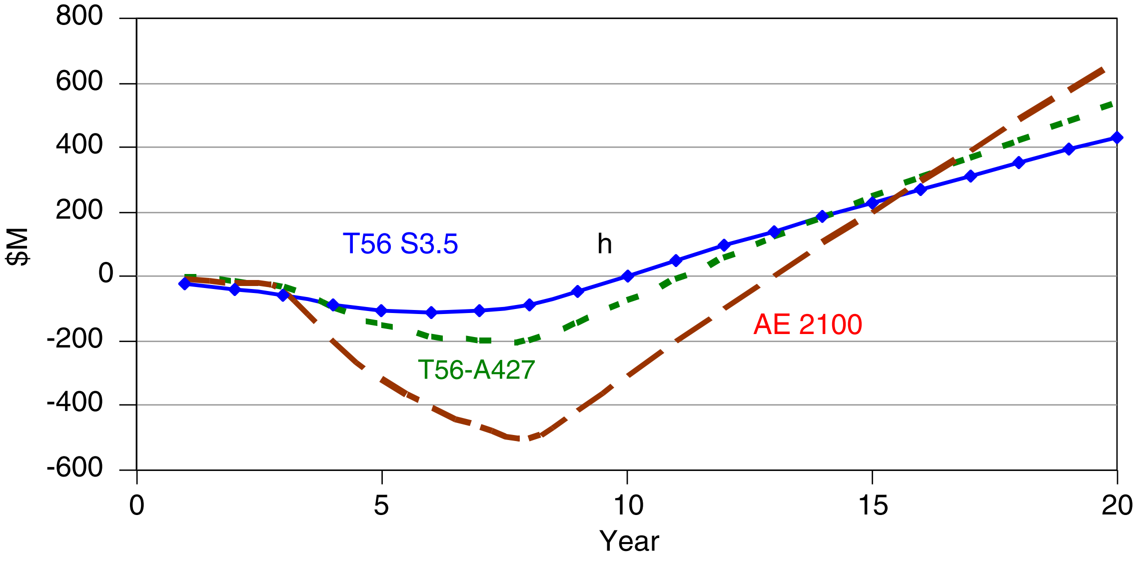

FIGURE F-1 Cash flow for C-130 re-engining options. SOURCE: Rolls-Royce.

TABLE F-2 Cost Assumptions

	Base		
Fuel burn/hr/engine (gal)	200		
Fuel cost per gallon ($)	2.20		
Maintenance cost/engine flight hour ($)	239		
No. of aircraft	267		
Annual flight hours	469		
Normal overhaul (hours on wing)	2,426		
	T56-S3.5	T56-A427	AE 2100
Upgraded fleet		—	—
Fuel saving (%)	8	13	28
Maintenance savings (%)	30	40	50
Kit cost/engine (relative)[a]	0.5	0.67	1.00
Relative cost (%)	50	67	100
Program costs (million $)			
Engine development	50	17	30
Flight qualification	5	10	10
Production preparation	5	5	5
Support preparation	2	2	2
Financial assumptions (%)			
Discount rate	7	7	7
Fuel cost escalation	5	5	5
Maintenance escalation	5	5	5
Key output data (discounted $)			
Upgrade rate (%)	19	19	19
Fuel saved (million gal)	111	181	390
Investment (million $)	187	351	743
Fuel cost savings (million $)	204	331	714
Maintenance savings (million $)	416	554	693
Net present value (million $)	432	535	664
Max negative cashflow (million $)	(109)	(203)	(503)

[a] Costs are expressed here as relative to avoid the use of proprietary data.

SOURCE: Rolls-Royce.

TABLE F-3 Fuel Savings Relative to Investments

	T56-S3.5	T56-A427	AE 2100	PW150
Annual fuel savings (million $)	8.04	13.06	28.13	27
Fuel savings (gal/yr/million $ [nonrecurring cost])	140,992	384,100	598,467	280,000

SOURCE: Egbert and York (2006).

and lighter than the AE 2100 (Croswell, 2006). The fuel consumption rate of the PW150 is slightly higher than that of the AE 2100. A more detailed study including installation, operational, and financial analysis is needed to make a selection between these two candidates.

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Appendix G

Sensitivity Analysis

Tables G-1, G-2, and G-3 provide the relevant columns of Tables 5-7 and 5-8 for three levels of fuel savings: 100 percent, 90 percent, and 50 percent of the estimate. All these are for a burdened fuel cost of \$2.50/gal. Tables G-1, G-2, and G-3 are for annual increases in fuel cost of 3 percent, 6 percent, and 9 percent, respectively.

Tables G-4, G-5, G-6, and G-7 give the relevant sensitivities in the estimates corresponding to Table 5-9 for total burdened per gallon costs of \$5, \$10, \$20, and \$40, respectively. The direct fuel cost component of \$2.50 increases at 6 percent per year, and the remainder (overhead component) increases at 3 percent per year, as stated in Chapter 5 text.

TABLE G-1 Sensitivity of NPV Results in Tables 5-7 and 5-8 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, with Fuel Cost Increasing at 3%/yr[a,b]

Candidate Aircraft/Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million $)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	17.7	19.2	32.3	203	59	−515
C-130H/PW150[d]	19.5	21.3	36.5	37	−91	−604
B-1/F119/5.0	>60	>60	>60	−1,029	−1,055	−1,161
E-3/CFM56-2B-1	22.2	23.3	29.0	−34	−47	−100
E-3/JT8D-219	36.3	37.8	45.8	−157	−164	−192
E-3/CFM56-7B22	16.5	17.3	21.9	78	57	−30
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	45.1	48.2	>60	−532	−555	−647
KC-135D/E: JT8D-219	>60	>60	>60	−769	−784	−845
KC-135D/E: CFM56-7B22	31.6	33.4	44.3	−378	−411	−543
B-52/F117-PW-100 [4]	20.6	22.0	31.3	−27	−83	−309
B-52/CF34-10A [8]	28.4	29.8	37.2	−361	−397	−543
B-52/CFM56-5C2 [4]	16.1	17.0	22.0	224	163	−81
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	>60	>60	>60	−1,318	−1,344	−1,446
C-130H: T56-A427 Mod[d]	17.8	19.3	31.0	107	31	−272
C-130H: T56-S3.5 Mod[d]	26.1	28.4	47.7	−184	−231	−417
B-1/F101 Mod	8.0	8.2	9.1	470	439	313
KC-10/CF6-50 Mod	3.8	3.8	3.9	325	324	316

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] Fuel cost is $2.50 per gallon.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-2 Sensitivity of NPV Results in Tables 5-7 and 5-8 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, with Fuel Cost Increasing at 6%/yr[a,b]

Candidate Aircraft/ Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million $)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	14.4	15.4	22.6	817	612	−208
C-130H/PW150[d]	15.5	16.6	24.6	585	402	−330
B-1/F119/5.0	51.1	55.2	>60	−922	−959	−1,107
E-3/CFM56-2B-1	19.0	19.9	25.1	20	1	−73
E-3/JT8D-219	29.4	30.7	37.9	−128	−138	−178
E-3/CFM56-7B22	14.5	15.2	19.3	165	135	14
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	32.3	34.1	45.3	−438	−471	−600
KC-135D/E: JT8D-219	47.9	50.7	>60	−707	−728	−814
KC-135D/E: CFM56-7B22	24.9	26.2	34.3	−243	−289	−475
B-52/F117-PW-100 [4]	17.0	18.0	24.6	206	126	−193
B-52/CF34-10A [8]	23.5	24.6	31.0	−211	−263	−468
B-52/CFM56-5C2 [4]	14.1	14.8	19.1	475	389	45
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	56.6	>60	>60	−1,213	−1,249	−1,394
C-130H: T56-A427 Mod[d]	14.6	15.5	22.5	431	323	−110
C-130H: T56-S3.5 Mod[d]	19.7	21.1	30.6	15	−51	−318
B-1/F101 Mod	7.7	7.9	8.8	610	565	383
KC-10/CF6-50 Mod	3.8	3.8	3.9	333	330	320

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] Fuel cost is $2.50 per gallon.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-3 Sensitivity of NPV Results in Tables 5-7 and 5-8 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, with Fuel Cost Increasing at 9%/yr[a,b]

Candidate Aircraft/ EngineCombination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million $)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	12.4	13.1	18.1	1,715	1,420	240
C-130H/PW150[d]	13.2	14.0	19.4	1,387	1,124	71
B-1/F119/5.0	33.5	35.4	47.0	–767	–820	–1,030
E-3/CFM56-2B-1	16.6	17.4	21.8	98	72	–34
E-3/JT8D-219	24.5	25.5	31.4	–87	–101	–157
E-3/CFM56-7B22	13.0	13.6	17.2	291	248	77
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	25.4	26.7	34.2	–301	–347	–531
KC-135D/E: JT8D-219	34.3	35.9	45.5	–616	–647	–768
KC-135D/E: CFM56-7B22	20.6	21.6	27.7	–46	–112	–376
B-52/F117-PW-100 [4]	14.6	15.3	20.4	545	431	–23
B-52/CF34-10A [8]	19.9	20.8	26.1	7	–66	–359
B-52/CFM56-5C2 [4]	12.6	13.2	16.8	841	718	228
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	36.6	38.5	50.2	–1,060	–1,112	–1,317
C-130H: T56-A427 Mod[d]	12.6	13.3	18.2	905	750	127
C-130H: T56-S3.5 Mod[d]	16.3	17.2	23.5	307	211	–172
B-1/F101 Mod	7.4	7.6	8.5	815	749	486
KC-10/CF6-50 Mod	3.8	3.8	3.9	343	339	325

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] Fuel cost is $2.50 per gallon.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-4 Sensitivity of NPV Results in Table 5-9 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, at a Burdened Fuel Cost of \$5 per Gallon[a,b]

Candidate Aircraft/ Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million \$)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	10.1	10.8	15.7	2,254	1,905	510
C-130H/PW150[d]	10.9	11.6	17.1	1,869	1,557	311
B-1/F119/5.0	36.6	40.1	>60	–658	–721	–975
E-3/CFM56-2B-1	14.5	15.3	20.4	154	122	–7
E-3/JT8D-219	23.3	24.6	32.1	–58	–75	–142
E-3/CFM56-7B22	10.9	11.6	15.4	380	329	121
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	24.5	26.1	36.6	–210	–265	–485
KC-135D/E: JT8D-219	37.2	39.9	57.3	–556	–592	–738
KC-135D/E: CFM56-7B22	18.7	19.9	27.4	86	6	–311
B-52/F117-PW-100 [4]	12.2	13.0	18.4	771	635	90
B-52/CF34-10A [8]	18.1	19.1	25.5	153	65	–286
B-52/CFM56-5C2 [4]	10.6	11.1	15.0	1,085	938	350
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	42.3	46.0	>60	–957	–1,019	–1,266
C-130H: T56-A427 Mod[d]	10.4	11.0	15.9	1,188	1,004	269
C-130H: T56-S3.5 Mod[d]	13.9	14.8	22.0	481	368	–85
B-1/F101 Mod	6.6	6.9	7.9	924	847	540
KC-10/CF6-50 Mod	3.6	3.6	3.8	351	346	329

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] The direct fuel cost component of \$5.00 increases at 6 percent per year, and the overhead increases at 3 percent per year.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-5 Sensitivity of NPV Results in Table 5-9 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, at a Burdened Fuel Cost of \$10 per Gallon[a,b]

Candidate Aircraft/ Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million \$)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	7.2	7.6	10.5	5,128	4,492	1,947
C-130H/PW150[d]	7.7	8.2	11.3	4,435	3,867	1,594
B-1/F119/5.0	22.0	24.2	42.4	−129	−246	−771
E-3/CFM56-2B-1	10.2	10.8	15.0	421	362	127
E-3/JT8D-219	16.7	17.7	24.6	83	52	−72
E-3/CFM56-7B22	7.8	8.3	11.3	811	716	337
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	16.6	17.8	26.2	247	146	−257
KC-135D/E: JT8D-219	25.2	27.2	41.5	−253	−320	−587
KC-135D/E: CFM56-7B22	12.9	13.8	19.7	743	598	18
B-52/F117-PW-100 [4]	8.4	8.9	12.6	1,902	1,652	655
B-52/CF34-10A [8]	12.8	13.6	18.9	881	720	78
B-52/CFM56-5C2 [4]	7.6	8.0	10.9	2,304	2,035	959
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	26.5	29.0	49.5	−445	−558	−1,009
C-130H: T56-A427 Mod[d]	7.4	7.9	10.7	2,702	2,367	1,026
C-130H: T56-S3.5 Mod[d]	9.6	10.1	14.5	1,413	1,207	381
B-1/F101 Mod	5.3	5.5	6.8	1,551	1,412	854
KC-10/CF6-50 Mod	3.3	3.3	3.6	387	379	347

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] The direct fuel cost component of \$10.00 increases at 6 percent per year, and the overhead increases at 3 percent per year.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-6 Sensitivity of NPV Results in Table 5-9 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, at a Burdened Fuel Cost of $20 per Gallon[a,b]

Candidate Aircraft/ Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million $)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	4.2	4.5	7.2	10,877	9,666	4,821
C-130H/PW150[d]	4.7	5.1	7.8	9,567	8,486	4,161
B-1/F119/5.0	12.6	13.7	23.0	927	705	−183
E-3/CFM56-2B-1	7.1	7.5	10.4	955	843	394
E-3/JT8D-219	11.1	11.9	17.1	366	306	69
E-3/CFM56-7B22	5.7	5.9	7.9	1,673	1,492	768
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	10.8	11.6	17.1	1,160	968	200
KC-135D/E: JT8D-219	15.8	17.0	26.4	352	225	–284
KC-135D/E: CFM56-7B22	8.7	9.2	13.2	2,057	1,781	675
B-52/F117-PW-100 [4]	6.1	6.4	8.6	4,126	3,687	1,785
B-52/CF34-10A [8]	8.8	9.3	13.0	2,336	2,030	806
B-52/CFM56-5C2 [4]	5.5	5.9	7.7	4,742	4,229	2,178
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	15.4	16.8	28.0	580	364	–497
C-130H: T56-A427 Mod[d]	4.5	4.9	7.5	5,731	5,093	2,540
C-130H: T56-S3.5 Mod[d]	6.5	7.1	9.7	3,277	2,884	1,313
B-1/F101 Mod	4.3	4.3	5.3	2,807	2,542	1,482
KC-10/CF6-50 Mod	3.1	3.1	3.3	460	445	384

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] The direct fuel cost component of $20.00 increases at 6 percent per year, and the overhead increases at 3 percent per year.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.

TABLE G-7 Sensitivity of NPV Results in Table 5-9 to Realizing 100%, 90%, and 50% of Baseline Expectations for Fuel Savings, at a Burdened Fuel Cost of $40 per Gallon[a,b]

Candidate Aircraft/ Engine Combination	Time to Recoup Investment (yr)[c]			Cash Flow at 20-yr Point (million $)[c]		
	100%	90%	50%	100%	90%	50%
Re-engining						
C-130H/AE 2100[d]	2.5	2.9	4.2	22,373	20,012	10,570
C-130H/PW150[d]	3.1	3.3	4.7	19,832	17,724	9,293
B-1/F119/5.0	7.8	8.3	12.8	3,041	2,607	874
E-3/CFM56-2B-1	5.2	5.4	7.1	2,023	1,804	928
E-3/JT8D-219	7.4	7.9	11.2	930	814	351
E-3/CFM56-7B22	4.0	4.2	5.7	3,397	3,043	1,630
E-8/CFM56-2B-1[e]	–	–	–	–	–	–
E-8/JT8D-219[e]	–	–	–	–	–	–
E-8/CFM56-7B22[e]	–	–	–	–	–	–
KC-135D/E: CFM56-2B-1	7.3	7.7	10.9	2,987	2,612	1,113
KC-135D/E: JT8D-219	9.9	10.6	16.0	1,563	1,314	321
KC-135D/E: CFM56-7B22	6.2	6.5	8.8	4,686	4,147	1,990
B-52/F117-PW-100 [4]	3.9	4.2	6.1	8,683	7,755	4,046
B-52/CF34-10A [8]	6.3	6.6	8.8	5,248	4,650	2,261
B-52/CFM56-5C2 [4]	3.6	3.8	5.5	9,618	8,617	4,616
C-5/CF6-80C2 (F103-GE-102)[f]	–	–	–	–	–	–
Engine modification						
KC-135R/T: CFM56-2B-1 (Mod)	9.4	10.1	15.7	2,629	2,209	527
C-130H: T56-A427 Mod[d]	3.1	3.2	4.5	11,788	10,544	5,569
C-130H: T56-S3.5 Mod[d]	4.0	4.3	6.5	7,004	6,239	3,177
B-1/F101 Mod	4.1	4.1	4.3	5,317	4,801	2,737
KC-10/CF6-50 Mod	3.0	3.0	3.1	606	576	457

NOTE: The engine cost estimates presented are derived from correlations developed for historical military engines and may not reflect the current fair market prices of commercial engines considered in this study. Engine cost estimates vary widely, and the estimates presented may vary by as much as 100 percent from estimates developed by other independent sources such as the IBA Engine Value Book 2005 as reported by *Euromoney Institutional Investor*, May 1, 2005.

[a] Values corrected after release of the January 31, 2007, prepublication version of the report.

[b] The direct fuel cost component of $40.00 increases at 6 percent per year, and the overhead increases at 3 percent per year.

[c] Shading indicates a recouping of investment costs in less than 20 years and thus a positive cash flow at the 20-year point.

[d] The fuel savings noted for the C-130 with new or modified engines are based on the aircraft being flown at the optimal altitude and airspeed for the selected engines and propellers. The flexibility exists in most C-130 missions for the aircraft to be operated at the best range or fuel consumption conditions. The other aircraft and engines considered in the study are operated at their prescribed mission conditions.

[e] E-8 re-engining already ongoing.

[f] C-5 re-engining already ongoing.