Military Jet Engine Acquisition

Technology Basics and Cost-Estimating Methodology

Obaid Younossi, Mark V. Arena, Richard M. Moore
Mark Lorell, Joanna Mason, John C. Graser

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PREFACE

In recent years, the affordability of weapon systems has become increasingly important to policymakers in the Department of Defense and U.S. Congress. Aerospace industry analysts and some government officials have asserted that government cost estimates are based on outdated methods that do not account for the latest technological innovations. The authors of this report present the results of a RAND research study to update the methods for estimating military jet engine costs and development time.

This report is one of a series from a RAND Project AIR FORCE research project called “The Cost of Future Military Aircraft: Historical Cost Estimating Relationships and Cost Reduction Initiatives.” The purpose of the project, which is part of the Resource Management Program, is to improve the tools available to the U.S. Air Force for estimating the cost of future weapon systems. The authors provide insights into military engine technology, the military aircraft acquisition process, and parametric cost-estimating methodologies.

This study draws from databases from various Air Force, Navy, and military engine contractors and interviews with government experts from the Air Force Research Laboratory (AFRL), Aeronautical Systems Center/Engineering (ASC/EN), Naval Air Systems Command, and industry experts from General Electric, Pratt and Whitney, and Rolls-Royce (North America).

This report should be of interest to the cost-analysis community, the military aircraft acquisition community, and acquisition policy professionals in general.

Lieutenant General Stephen B. Plummer, SAF/AQ, sponsored this project. The project's technical point of contact is Jay Jordan, technical director of the Air Force Cost Analysis Agency.

Other RAND Project AIR FORCE reports that address military aircraft cost-estimating issues are:

- *Military Airframe Acquisition Costs: The Effects of Lean Manufacturing* by Cynthia R. Cook and John C. Graser (MR-1325-AF). In this report, the authors examine the package of new tools and techniques known as "lean production" to determine if it would enable aircraft manufacturers to produce new weapon systems at costs below those predicted by historical cost-estimating models.
- *An Overview of Acquisition Reform Cost Savings Estimates* by Mark A. Lorell and John C. Graser (MR-1329-AF). For this report, the authors examined the relevant literature and conducted interviews to determine whether estimates on the efficacy of acquisition reform measures are sufficiently robust to be of predictive value.
- *Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes* by Obaid Younossi, Michael Kennedy, and John C. Graser (MR-1370-AF). In this report, the authors examine cost-estimating methodologies and focus on military airframe materials and manufacturing processes. This report provides cost estimators with factors that are useful in adjusting and creating estimates that are based on parametric cost-estimating methods.

PROJECT AIR FORCE

Project AIR FORCE, a division of RAND, is the Air Force Federally Funded Research and Development Center (FFRDC) for studies and analyses. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is performed in four programs: Aerospace Force Development; Manpower, Personnel, and Training; Resource Management; and Strategy and Doctrine.

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SUMMARY

Good cost estimates contribute significantly to an effective acquisition policy. RAND has a long history of producing cost-estimating methodologies for military jet engines.[1] Two of RAND's more recent studies of turbine engine costs are Nelson (1977) and Birkler, Garfinkle, and Marks (1982). This report updates those earlier studies by incorporating cost and technical data on recent engine development and production efforts. We analyzed this information and produced a set of parametric relationships to estimate turbofan engine development costs, development schedules, and unit production costs.

In this analysis, we have extended and improved upon earlier RAND analyses in two key ways:

- The previous RAND studies grouped turbojet and turbofan engines into the same population. To provide a more homogeneous population, we focused exclusively on parametric relationships for turbofan engines in this study (because pure turbojet engines are largely no longer used in modern aircraft).
- In the previous studies, it was often not clear how the data from a particular engine family was treated. In our analysis, we treat each model (or "dash number") as a separate observation. We explicitly consider how derivative engines relate to first-of-a-kind engines.

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[1] For instance, Watts (1965); Large (1970); Anderson and Nelson (1972); Nelson and Timson (1974); Nelson (1977); Nelson et al. (1979); and Birkler, Garfinkle, and Marks (1982) are RAND studies focused exclusively on jet engine costs.

In our statistical analysis, we explore most of the possible performance, programmatic, and technology parameters that affect development and production costs and the development schedules of engines. We employ least-squares regression methods to develop a series of parametric relationships for forecasting the development cost, development time, and production cost of future military turbofan engine programs.

TECHNICAL BACKGROUND

The first part of this report provides basic concepts on how engines operate, the parameters used to compare engines, development process alternatives, and likely future trends in jet engine technologies. An understanding of these concepts, alternatives, and trends should help both program managers and cost analysts to employ the cost-estimating relationships (CERs) described in the second part of this report and should facilitate conversations about jet engines and what affects their costs.

We describe various engine performance parameters and development approaches. The engine community uses these parameters to rate the quality and performance of individual components used as independent variables in CERs. In addition, we discuss other factors such as environmental requirements (for pollution control, noise abatement, and such), new performance requirements (stealth and thrust vectoring), and maintenance requirements (such as prognostic health monitoring systems and reliability and maintainability improvements programs) that influence an engine's life-cycle costs and have implications for the engine CERs explored in this report.

While these factors and other new technologies could increase or decrease costs, it is nearly impossible to identify every future cost driver when a CER is being developed. However, because the CERs are often based on historical data and performance metrics, they do not reflect the influences of these new factors on costs. Therefore, an analyst should consider the influence of these new factors when forecasting the cost of future military engines.

COST-ESTIMATING METHODS

The second part of this report presents a discussion on how cost-estimating methods are developed. We discuss the principal cost-estimating methods—i.e., *analogy, bottom-up,* and *parametric.* The bottom-up approach relies on detailed engineering analysis and calculations to determine a cost estimate. Another approach related to the bottom-up method is estimating by analogy. With this approach, an analyst selects a system that is similar to the system undergoing the cost analysis and makes adjustments to account for the differences between the two systems. The third approach is the parametric method, which is based on a statistical technique that attempts to explain the changes in the dependent variable (e.g., cost or development schedule) as a function of changes in several independent variables, such as intrinsic engine characteristics (e.g., size, technical/performance characteristics, or risk measures). We selected the parametric method for our analyses in this study.

We next focus on the estimation of parameters for the various turbofan engines in our database, data normalization and our efforts at validating the data, and the addition of new observations to update a series of parametric cost-estimating relationships published in earlier RAND studies. Finally, we describe a series of technical risk and maturity measures that we applied to each engine in our database.

We describe our statistical analysis and present a series of parametric estimating methods for aircraft engine acquisition costs and development times. We determine each of the cost-estimating relationships through a series of stepwise and ordinary least-square regression methods. We present cost-estimating relationships for aircraft turbofan engine development cost, development time, and production cost.

Finally, to illustrate how the various estimating relationships presented in this report can be used to generate cost projections, we provide examples of two notional engines—a new engine with advanced technologies and a derivative engine that employs more-evolutionary technological advances.

RESULTS AND FINDINGS

Our results indicate that rotor inlet temperature is a significant variable in most of the reported cost estimating relationships. Full-scale test hours and whether an engine is new or derivative are significant drivers of development time estimating relationships.

Our projections also indicate that a new advanced-technology engine design would have significantly higher development costs and would take longer to develop than a derivative engine using evolutionary technologies.

Disappointingly, the residual error for the development-cost and development-time estimating relationships remains rather high, particularly for the derivative engines. Therefore, these relationships are most useful at the conceptual stage of a development program. On the other hand, the parametric relationship presented for estimating the production costs can be used with more confidence. However, we still recommend this approach only for the conceptual phase or in the event quick estimates are required and detail information is lacking.

In all cases, simple performance parameters and technical risk measures, such as full-scale test hours and new-engine-versus-derivative-engine parameters, were the most significant factors. However, residual errors for development time and engine development costs are high, and readers are cautioned from using these CERs anywhere other than at the conceptual stage of aircraft development.

ACKNOWLEDGMENTS

The authors of this study had extensive discussions with knowledgeable aerospace professionals in many government and industry organizations. Many of them generously provided us with data for the study and shared their insights with us. Although they are too numerous to mention individually, we offer a thank-you to everyone who shared information with us. However, we would like to acknowledge those organizations that we visited and our principal points of contact.

The government organizations we visited and our principal contacts there were:

- Office of the Assistant Secretary of the Air Force for Acquisition (SAF/AQ): Lieutenant General Stephen B. Plummer
- Air Force Cost Analysis Agency: Joseph Kammerer, director, and Jay Jordan, technical director
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- Naval Center for Cost Analysis, Washington, D.C.: William Stranges
- Aeronautical Systems Center, Propulsion Division: James Crouch
- Air Force Research Laboratory: Bill Stage and Charles Skira.

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- General Electric Aircraft Engines, Cincinnati: Joe Carroccio.
- Pratt & Whitney Aircraft Engines, East Hartford, Connecticut: Don Nichols
- Rolls-Royce/Allison Advanced Development Company, Indianapolis: David Quick.

In singling out someone who provided extensive engine data, and without whom this study would not be possible, we acknowledge Al Pressman from the Naval Air Systems Command Cost Department. He made this study possible through his insight and careful collection of data over many years. The cost-estimating community owes him many thanks.

Our RAND colleagues Giles Smith and Fred Timson reviewed this document. Their comments and thorough review occasioned many changes and improved the quality and the content of this report. For that we are grateful. We also would like to thank our colleagues Bob Roll, PAF Program Director, Resource Management, for his leadership; Jerry Sollinger, for his help with documentation; Tom Sullivan, for lending a hand with data analysis; Brad Boyce, our summer associate; Michele Anandappa, for research and administrative assistance; and Nancy DelFavero, who edited the report.

ACRONYMS

AADC	Allison Advanced Development Company
AEP	Alternate Engine Program
AFRL	Air Force Research Laboratory
AMT	Accelerated mission testing
ANN	Artificial neural network
APU	Auxiliary power unit
ASC/EN	Aeronautical Systems Center/Engineering
ATEGG	Advanced Turbine Engine Gas Generator (program)
ATES	Advanced Technical Engine Studies (program)
ATF	Advanced Tactical Fighter
BPR	Bypass ratio
CAD/CAM	Computer-aided design/computer-aided manufacturing
CCA	Cooled cooling air
CCDR	Contractor Cost Data Report
CCI	Capability/Cost Index
CER	Cost-estimating relationship
CESAR	Component and engine structural assessment research

CFD	Computational fluid dynamics
CMC	Ceramic matrix composites
DARPA	Defense Advanced Research Programs Agency
DoD	Department of Defense
EMD	Engineering and Manufacturing Development
ESBI	Engine Supplier Base Initiative
˚F	Degrees Fahrenheit
FETT	First engine to test
FIS	First in series
FOD	Foreign object damage
GD	General Dynamics
GE	General Electric
HCF	High cycle fatigue
HPT	High-pressure turbine
IBR	Integrally bladed rotor
IHPTET	Integrated High Performance Turbine Engine Technology (Program)
IOC	Initial operational capability
IRP	Intermediate rating point
ISG	Integral starter-generator
ISR	Initial Service Release
JSF	Joint Strike Fighter
JTDE	Joint Technology Demonstrator Engine
kg	Kilogram(s)
kN	KiloNewton(s)
kw	Kilowatt(s)
LCF	Low cycle fatigue

LO	Low observable
LPR	Low-production rate
LPT	Low-pressure turbine
MAI	Metals Affordability Initiative
MQT	Model qualification test
N	Newton
NADC	Naval Air Development Center
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NCCA	Naval Center for Cost Analysis
OCR	Operational Capability Release
OEM	Original equipment manufacturer
OLS	Ordinary least squares
OPR	Overall pressure ratio
O&S	Operations and support
PFR	Preliminary Flight Release
P&W	Pratt & Whitney
R&D	Research and development
RAF	Royal Air Force
RIT	Rotor inlet temperature
RLM	Reichsluftfahrt-Ministerium
RMSE	Root mean square error (residual error)
SFC	Specific fuel consumption
SHP	Shaft horsepower
SI	Systeme Internationale
SOA	State-of-the-art
STOVL	Short takeoff and vertical landing

TAC	Total accumulated cycles
TBC	Thermal barrier coatings
TOA	Time of arrival
TRL	Technology readiness level
TSFC	Thrust specific fuel consumption
UEET	Ultra Efficient Engine Technology
UK	United Kingdom
VAATE	Versatile Affordable Advanced Turbine Engine (Initiative)

Chapter One

INTRODUCTION

STUDY BACKGROUND AND PURPOSE

Realistic cost estimates for military aircraft play an important role in developing sound budgets and in contributing to an effective acquisition policy. RAND has a long tradition of developing cost-estimation techniques and has published a number of widely read reports on the topic.[1] As design approaches and manufacturing processes and materials used in engine production change and new information on aircraft engine technology becomes available, these cost-estimation techniques should be updated. This report presents the results of a RAND research project to develop a methodology for estimating military engine costs.

This work is part of an ongoing RAND research project on military aircraft costs. Three earlier publications stemming from this project are relevant to the discussion in this report. One of those three reports, Cook and Graser (2001), is on the effect of lean manufacturing on airframe costs, Another report, Lorell and Graser (2001), analyzes the effect of acquisition reform on military aircraft costs. The third report, Younossi, Kennedy, and Graser (2001), addresses the effect of advanced materials and manufacturing methods on airframe costs.

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[1] Watts (1965), Large (1970), Anderson and Nelson (1972), Nelson and Timson (1974), Nelson (1977), Nelson et al. (1979), and Birkler, Garfinkle, and Marks (1982).

UPDATING OF PREVIOUS STUDY METHODS

The methodology for estimating aircraft engine costs has traditionally been based on historical cost data on various aircraft engines; typically, the data are on development and production costs and aircraft quantities produced by engine type. These costs are used as the dependent variables in statistical regression analyses. Explanatory variables or estimating parameters typically include such factors as engine turbine inlet temperature, airflow, thrust-to-weight ratio, and some technology and maturity proxies. The products of the regression analysis are equations that are referred to as "cost-estimating relationships" (CERs).

The most recent RAND studies that used this approach were Nelson (1977) and Birkler, Garfinkle, and Marks (1982). This study updates the 1977 and 1982 studies in three ways:

1. We use a more recent set of cost data provided by the Naval Air Systems Command (NAVAIR) to capture the effect of technological evolution that has occurred over the past two decades. Changes in technology that have occurred over the past five decades are summarized in Table 1.1.
2. We segregate the turbofan engine cost data from the turbojet and turboshaft cost data. This approach provides a more homogenous population for the parametric cost analysis.
3. We treat each engine model (or "dash number") as a separate observation, unlike the earlier studies, which did not explicitly address how to treat a family of engine types.

THE ORGANIZATION AND CONTENT OF THIS REPORT

This report is divided into two parts: "Engine Basics and Performance Parameters" in Chapter Two and Chapter Three, and "Data Analysis and Cost-Estimating Techniques" in Chapters Four through Six. In Chapter Seven, we present our overall conclusions.

Chapter Two presents an introductory discussion of jet engine basics and engine performance parameters that affect costs. The government and industry engine acquisition and engineering communities use a variety of parameters to assess and compare the quality and performance of jet engines and their components. Some parameters describe the physical characteristics of an engine (such as weight, length, and material composition) whereas others describe the performance of an engine (such as thrust) and other performance and design characteristics of individual components (such as combustor efficiency and maximum fuel-to-air ratio). Chapter Three describes emerging engine technologies and industry and government initiatives that may influence the costs of the future engines.

The first two chapters provide background information for a general audience or for cost analysts who are unfamiliar with the basics of engine technologies. Also, an understanding of these concepts should enable program managers and cost analysts to employ the cost-estimating relationships described in the second part of this report and facilitate discussions on jet engines and what affects their costs.

Readers who do not need the basic information presented in Chapters Two and Three and are nterested primarily in our cost analysis can begin at Chapter Four, which presents an overview of our principal cost-estimating methods—*analogy, bottom-up,* and *parametric.* Chapter Five discusses technical estimating parameters, the data used in our analysis, and the data normalization process. Chapter Six presents a statistical analysis of historical turbofan engine cost data and the resulting parametric-cost and schedule-estimating relationships (i.e., the equations that result from our regression analysis). Chapter 6 concludes by integrating these estimating methods into a notional example for projecting the costs of all future military engines. Chapter Seven presents our conclusions, and the appendices provide substantial historical background on the development of military jet engines.

Table 1.1

Engine Technological Evolution

	1960s	1970s	1980s	1990s	2000s
Materials/ Processes	Superalloys Nickel-based alloys Titanium-based alloys	Low-temperature composites Directional solidification Powder metallurgy Nondestructive inspection techniques	Single crystals Thermal barrier coatings Computerized numerical control machining Automated vacuum welding	Intermetallics Near-net shape Advanced coatings Ceramics for low-stress parts	High-temperature composites Laser shot peening High-cycle fatigue reduction Blisk tuning/repair Automatic prognostics and health management
Tools for Design	Fracture mechanics	Component optimization	Computer-aided design/ computer-aided manufacturing (CAD/CAM) Finite element analysis Computational fluid dynamics Damage tolerance	Rapid prototyping Advanced sensors	Metal prototyping Engine testing integrated with aircraft simulators Complete engine computational fluid dynamics (CFD) modeling

Table 1.1—Continued

	1960s	1970s	1980s	1990s	2000s
Engine Technologies	Variable stator geometry Blade cooling Canannular combustors Rotatable vertical/short takeoff and landing nozzles Afterburning turbofans	Annular combustors Modular design High-bypass turbofans	Diagnostics Digital electronic control Low-aspect-ratio blades Low-emissions combustors Low-observable inlets and nozzles	Blisks (bladed disks, or integrally bladed rotors) Hollow fan blades Two-stage combustors Variable engine cycles 2-dimension vectoring nozzles Counter-rotating spools	Premixed combustors Integrated flight and propulsion controls Multipoint fuel injectors High-temperature fuels Fluidic nozzles Integral starter generator
Tactical Aircraft Engine Model Numbers	TF30 F402	F100 F401 F101 TF34	F110 F404	F119 F120 F414	F135

PART I: ENGINE BASICS AND PERFORMANCE PARAMETERS

Chapter Two

JET ENGINE BASICS, METRICS, AND TECHNOLOGICAL TRENDS

This chapter provides a basic overview of jet engine technologies and the metrics used to compare them. This background information on engine components and performance parameters should be useful in interpreting the engine data and cost-estimating relationships presented in Chapters Five and Six. In addition, some related emerging technologies and cost-reduction initiatives are also described in the next chapter to illuminate some factors that may influence the costs of future jet engines.

JET ENGINE BASICS

Jet engines operate on what thermodynamicists know as the *Brayton cycle.* The Brayton cycle consists of three distinct stages: compression (raising the pressure of the air entering an engine), heating (raising the temperature of the air to increase its energy greatly), and expansion (allowing the pressure of the flowing air and fuel combustion products to drop in order to extract energy and accelerate the flow).[1] While variations in hardware design and complexity exist, these three stages are normally achieved in jet engines by using the following processes:

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[1] More specifically, and from a theoretical perspective, the Brayton cycle consists of adiabatic compression of the working fluid (raising the pressure of the air, without external heating or cooling), heating the working fluid at a constant pressure, and adiabatic expansion of the working fluid (allowing the pressure to drop without external heating or cooling).

The pressure of the air entering an engine is raised as the air is initially slowed by the engine's *inlet*[2] and as it flows through the engine's *compressor*. Next, heating occurs in a *combustor,* where fuel is burned with the high-pressure air. Finally, expansion occurs as energy is extracted from the exhaust gases by a *turbine*. These gases accelerate through the engine's *nozzle* to produce thrust. The turbine extracts power from high-pressure and high-temperature combustion products (much like a windmill extracts energy from wind) to drive (turn) the rotating compressor. A small percentage of the turbine's power is also drawn off to run auxiliary systems, such as the oil pump, fuel pump, hydraulic pump, and alternator.

A jet engine produces *thrust* by making a net change in the velocity of the air that is moving through the engine. In the words of Sir Isaac Newton, for every action there is an equal and opposite reaction. As the engine "pushes" on the air to accelerate it, the air pushes back on the engine, providing thrust for the aircraft. This effect is illustrated by the basic thrust equation:

Thrust = mdot * (Vout – Vin)

where, mdot is the rate at which air moves through the engine (kilograms [kg]/second), Vout (meters/second) is the velocity of the flow leaving the exhaust nozzle (i.e., the flow's velocity relative to the nozzle), and Vin is the velocity of the air as it approaches the engine (which is also the aircraft's true airspeed).[3]

A *turbojet* is a basic jet engine that integrates the five primary components mentioned earlier (inlet, compressor, combustor, turbine, and nozzle). Some turbojets include a second combustor after the turbine, called an *afterburner* (or *augmentor*). The afterburner adds energy to the turbine discharge flow to maximize the thrust from the engine. The afterburner is usually engaged only when the maximum thrust is required because the fuel efficiency of a jet engine drops by a factor of three or four when the afterburner is at its maximum set-

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[2] Inlets slow the incoming air at most flight conditions. However, when the aircraft is parked with the engines running or is flying very slowly, the engine is actually accelerating the air as it sucks it into the inlet.

[3] For simplicity, these velocities are measured relative to a reference frame attached to the aircraft.

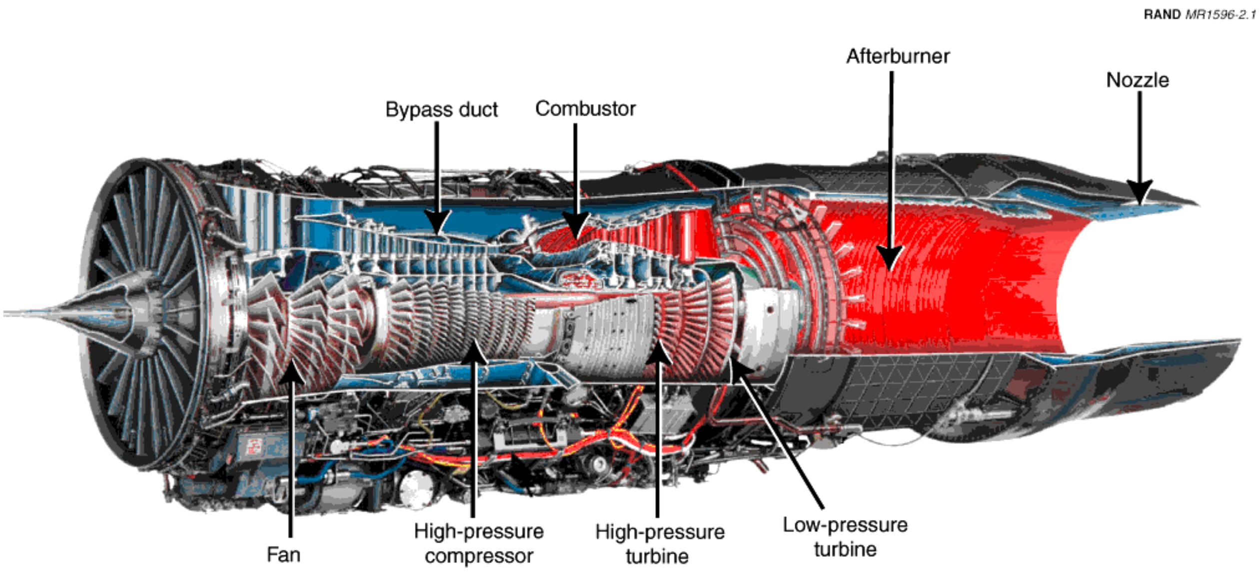
ting. Most early jet engines were turbojets. However, with some exceptions, such as some small and relatively inexpensive turbojets designed for one-time-use missile applications, modern jet engines have evolved into more-complicated devices called *turbofan engines.*

A turbofan engine is more complex and more efficient than a turbojet. A turbofan adds a second compressor, called a *fan,* a *low-pressure turbine* to drive the fan, and an annular-shaped *bypass duct* that allows part of the fan's discharge air to flow around the high-pressure compressor, combustor, and both turbines. The fan compresses air, much like the high-pressure compressor, and some of the air leaving the fan enters the high-pressure compressor, while the remainder flows through the bypass duct. This bypass air is eventually accelerated through a nozzle to produce thrust.

Figure 2.1 is a cutaway drawing of a Pratt & Whitney (P&W) F100-220 afterburning turbofan. The fan, high-pressure compressor, combustor, high-pressure turbine, low-pressure turbine, bypass duct, afterburner, and nozzle are labeled. (The inlet is not shown because each tactical aircraft would have a different inlet design.) The combination of high-pressure compressor, combustor, and high-pressure turbine is known as an engine's *core.*

In afterburning turbofans, the portion of the fan's air that passes through the bypass duct is remixed with the core's combustion products in the afterburner, before the mixture is accelerated through the nozzle. When maximum or near maximum thrust is necessary, the afterburner injects additional fuel into these flows as they are mixing, and then burns this air-fuel mixture before it reaches the nozzle. Due to fuel efficiency (flight duration and range) considerations, the afterburner is used only for takeoff and when maximum acceleration is needed for a short period of time. In fact, the F-22's afterburning turbofan (Pratt & Whitney F119-100) is powerful enough to allow this aircraft to supercruise (fly supersonically without afterburning).

Turbofans are the only engines on military fighter aircraft that are equipped with afterburners. Most of the engines flying on modern commercial airliners and similar wide-body and military aircraft are high-bypass-ratio (BPR) turbofans and do not use afterburners. The BPR is the ratio of the bypass airflow rate to the core airflow rate.



SOURCE: Pratt & Whitney, A United Technologies Company. Reproduced with permission.

Figure 2.1—Pratt & Whitney F100-220 Afterburning Turbofan

Therefore, a high-BPR turbofan engine has a relatively large diameter fan, which handles much more air than the high-pressure compressor it precedes. These high-BPR turbofans are significantly more fuel-efficient than turbojets or low-BPR turbofans. This increased efficiency makes the added size and complexity of a large fan and corresponding low-pressure turbine cost effective for many applications.[4] On the other hand, high-BPR turbofans have large diameters and relatively low thrust-to-weight ratios, requiring large nacelles on wings or large ducts through fuselages. This is incompatible with aircraft designed for supersonic flight due to the high drag and weight implications. Instead, fighter engines are typically designed with low BPRs (typically 0.3 to 0.8) to strike a balance between engine efficiency, diameter, and weight.

Turboprop and *turboshaft* engines also operate on variations of the Brayton cycle. These engines have cores similar to turbojet and turbofan cores. In addition, they typically have a low-pressure turbine that extracts most of the remaining available energy from the combustion products after they leave the core. This low-pressure turbine turns a shaft, which is not connected to a fan or compressor. Instead, this shaft is used to drive a propeller (turboprop) or a helicopter rotor (turboshaft).[5] Intuitively, it may be helpful to think of a turboprop as a turbofan with an extraordinarily large bypass ratio but without a nacelle around the propeller to form the bypass duct. At times, the visible presence of a propeller or rotor leads some to incorrectly as-

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[4] It is instructive to understand why a turbofan (especially a high-BPR turbofan) improves fuel efficiency. This is best understood by considering the definitions of kinetic energy (kinetic energy = mV^2) and momentum (momentum = mV) in the light of the thrust equation presented earlier (Equation 1). In these definitions, m is the mass of a moving object and V is its velocity. When fuel is burned to heat the air flowing through a jet engine, it increases the flow's internal energy, which is partially converted to kinetic energy in the engine's nozzle. Depending upon the bypass ratio of an engine design, a given change in kinetic energy can take the form of a small mass of air undergoing a large increase in V^2, or a large mass undergoing a small increase in V^2. However, as Equation 1 reveals, *thrust is produced in proportion to the change in velocity through the engine, not the change in velocity squared* (in other words, thrust increases in proportion to the increase in momentum [mV] rather than the increase in kinetic energy [mV^2]). When the fuel's energy is used to create a very large V^2, the thrust increases only by the square root of this increase (V). Therefore, it is most efficient to accelerate a large amount of air by a small increase in velocity, leading engine manufacturers to design turbofans with a high BPR, if practical for the aircraft's mission.

[5] Turboshafts are also used to drive other devices, such as the M-1 tank, Navy ships, and Brayton cycle power plants.

sume that these aircraft are powered by internal combustion engines like early propeller-driven aircraft, rather than by these forms of jet engines.

Like the turbofan or turbojet, these engines have a nozzle downstream of the low-pressure turbine, and the flow exiting this nozzle typically produces some thrust. However, the low-pressure turbine extracts so much of the flow's energy before it reaches the nozzle that the main propulsive effect is achieved by the propeller or helicopter rotor, rather than by the flow exiting this nozzle. Virtually all turboprop and turboshaft engines employ highly efficient gearboxes to reduce the power shaft's rotational speed to an RPM appropriate for the propeller, rotor, and other engine components.

JET ENGINE PARAMETERS

Several parameters have been defined and are used widely to characterize the quality and performance of jet engines. In many cases, these parameters also have the greatest affect on engine cost. The most common of these metrics are defined in this section.

Thrust from turbofans and turbojets is measured in pounds or Newtons (N). *Maximum thrust* is the highest level of thrust available from an engine. This level is achieved by positioning the throttle at maximum afterburner (if so equipped), by injecting water into the engine's airflow to increase thrust for takeoff on some turbojets and turbofans,[6] or by setting the throttle at a temporary "overspeed" maximum RPM, which may have a time or altitude restriction associated with it. Many engines do not use any of these augmentation techniques.[7]

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[6] This technique, which is no longer common, simply increases the mass ejected from the engine.

[7] Turboprop and high-bypass turbofan engines produce much higher thrust at very low speeds and altitudes (takeoff conditions) than at their higher subsonic cruise speeds and altitudes. This creates a good match with their thrust requirements with each of these conditions, negating much of the need for augmentation techniques to produce additional power at takeoff. In addition, the F-22's F119 afterburning turbofan has sufficient military thrust to permit supersonic cruising without lighting the afterburner (supercruising), which may greatly reduce the fraction of time this engine's afterburner is needed.

Military thrust is conventionally defined as the highest level of thrust produced by the engine without using these augmentation capabilities (e.g., with the afterburner turned off).

Shaft horsepower (SHP)(measured in horsepower, kilowatts (kw), and other units of power) is the "capability" metric for turboprop and turboshaft engines, analogous to a turbojet's or turbofan's thrust. The power transferred by a shaft is proportional to the product of the shaft's torque (foot-pounds, Newton-meters, and such) times its rate of rotation (revolutions per minute, radians per second, and such).

Specific fuel consumption (SFC) is the conventional fuel efficiency metric for jet engines. This metric assumes different forms. The two most common forms are described next.

For turbojets and turbofans, SFC is often referred to as the *thrust specific fuel consumption* (TSFC) and is the ratio of the fuel flow rate to the thrust. Clearly, low values of TSFC are good. Measured in pounds of fuel per hour/pounds of thrust,[8] which is usually shortened to 1/hour. In *Systeme Internationale* (SI) units, SFC is measured in units of kilograms of fuel per second/kiloNewtons of thrust). When only one value of TSFC is reported for an engine, it is often the TSFC corresponding to the military thrust level, rather than the maximum (augmented) thrust level.

Figure 2.2 illustrates the military thrust SFC advantage offered by turbofans compared with turbojets. The very low SFC engines indicated at the bottom of the figure are all high-BPR turbofans.

For turboshafts and turboprops, the most common form of this metric is the *power specific fuel consumption,* which is frequently written simply as SFC.[9] This form of SFC is the ratio of the engine's fuel flow rate to the shaft horsepower from the engine. (The units of this metric are written as 1/length but are most often reported as "pounds of fuel per hour per horsepower" and when reported in SI units "kilogram per hour per kilowatt.") Again, low values of SFC reflect an efficient engine.

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[8] For purposes of this discussion, the distinction between pound-mass and pound-force is ignored.

[9] This form of SFC is also referred to as *brake-power specific fuel consumption*.

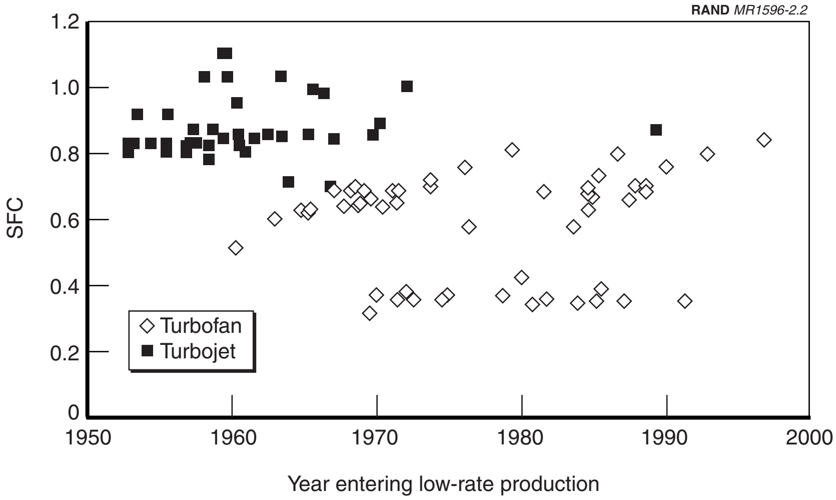

Figure 2.2—Turbojet and Turbofan Thrust-Specific Fuel Consumption Trends Since 1950

Thrust-to-weight ratio (dimensionless [pounds/pounds]) and *power-to-weight ratio* (normally reported in horsepower/pound) reveal the maximum performance available from an engine for each pound of engine weight for turbofans/turbojets and turboshafts/turboprops, respectively. These are useful metrics when comparing engines of different sizes. Increasing the thrust-to-weight or power-to-weight ratio in an engine design is desirable because it enhances overall aircraft performance and may reduce life-cycle costs. Figure 2.3 illustrates the steady increase in thrust-to-weight ratio for turbojets and turbofans over the past five decades. Modern tactical aircraft engines, which normally place a greater emphasis on performance than efficiency, have thrust-to-weight ratios of about eight to one. The design optimizations that provided superior SFCs through high BPRs, as shown in the Figure 2.2, understandably resulted in thrust-to-weight ratios of three to six.

The overall size of an engine is reflected in its *weight* (pounds) or *mass* (kg). Similarly, the *flow rate of air* through the engine (pounds

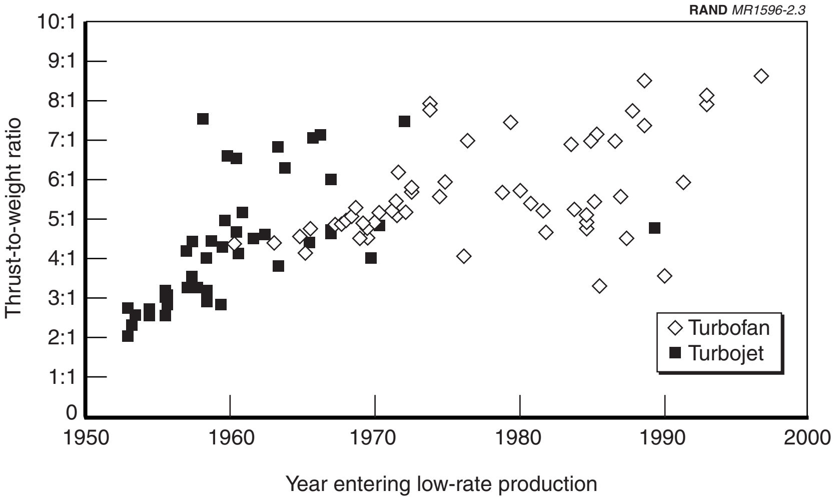

Figure 2.3—Turbojet and Turbofan Thrust-to-Weight Trends Since 1950

of air per second, or kg of air per second) is also an indication of the size of an engine and an indication of the size of inlet required.

Overall pressure ratio (OPR) is the dimensionless ratio of the pressure of the air exiting the high-pressure compressor to the pressure of the air entering the fan on a turbofan engine, or entering the compressor on a turbojet, turboprop, or turboshaft. High OPR contributes to high engine efficiency and, in turn, low SFC. However, raising engine OPR results in heavier and more costly engines because it normally requires additional compressor or fan stages and larger turbines. High OPR also produces design and manufacturing challenges, including small, geometrically complex high-pressure compressor airfoils that must endure higher temperatures in the last compressor stages. Figure 2.4 illustrates the steady and rapid increase in OPR for turbojets, turbofans, and turboshafts over the past five decades. The smaller core engines, including turboshafts, normally have lower OPRs.

Rotor inlet temperature (RIT) is the temperature of the air/fuel combustion products as they enter the high-pressure turbine's first row of rotating turbine blades (rotor), after having left the row of sta-

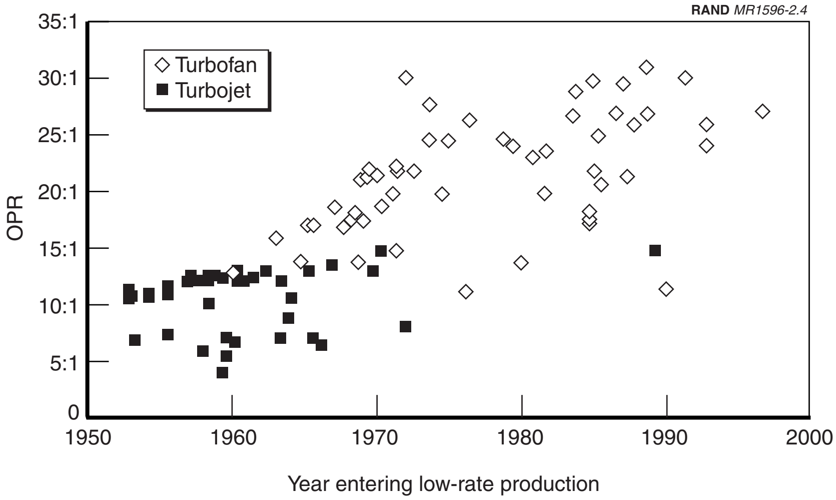

Figure 2.4—Turbojet and Turbofan Overall Pressure Ratio Trends Since 1950

tionary turbine blades (vanes) just downstream of the engine's combustor. A high RIT contributes to an engine's high thermal efficiency and high thrust-to-weight or power-to-weight ratio. Modern high-temperature turbine blades are typically made from single-crystal nickel-based superalloys. However, the operating temperature limits of these turbine materials are well below the RITs associated with most modern engines. In addition, the high centripetal forces caused by the rotational speeds of these rotor stages further limit their allowable operating temperatures. Therefore, a small stream of air bled from the high-pressure compressor is ducted through the hottest turbine blades (those farthest upstream) to cool them, and ceramic thermal barrier coatings (TBCs) are applied to the outside surfaces of these blades to insulate them from the hot combustion products. These two steps keep the structural materials of the blades at acceptable operating temperatures.[10] Because of the extraordinary techni-

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[10] Bleed-air cooling is accomplished using one or more of the following four cooling-scheme techniques:

cal challenges associated with thermally protecting these turbines, the RIT is a good indicator of the level of technology in a modern turbine engine.[11] Figure 2.5 illustrates the process of turbine blade cooling.

Figure 2.6 illustrates the steady and rapid increase in RIT for turbojets, turbofans, and turboshafts over the past five decades. Smaller engines, including turboshafts, normally have lower RITs.

Engine component life is measured in expected hours of operation. Many factors, including high temperatures, aerodynamic and mechanical stresses, erosion, corrosion, and other such factors, to which engine components are subjected can limit the length of time

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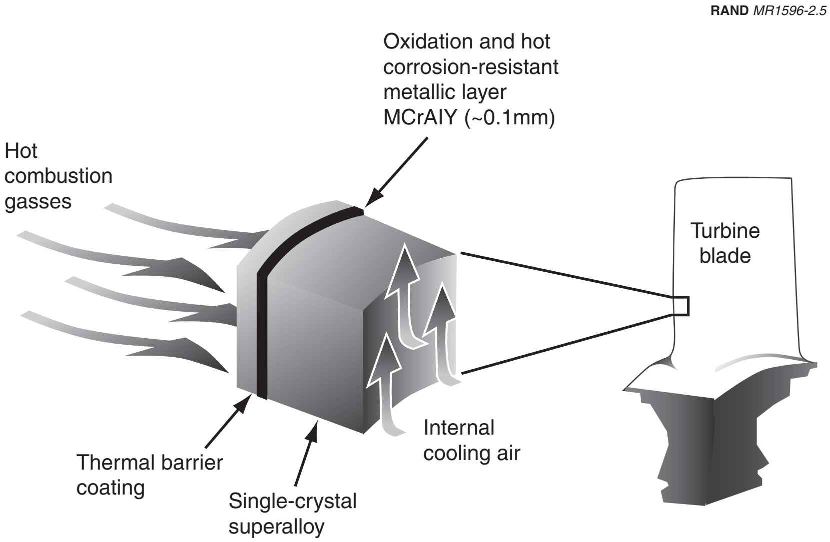
1. *Convection Cooling.* Relatively cool high-pressure air, bled from the compressor, passes through internal ducts in the turbine blades to absorb energy from the blade walls.
2. *Impingement Cooling.* The internal air passages inside the blade are oriented such that the air is directed forcefully onto the hottest internal surfaces, providing localized enhanced cooling where it is needed.
3. *Film Cooling.* Multiple holes in the blade's outer wall connect the blade's internal cooling cavities with its outer surface, allowing cool air to pick up heat as it passes through the wall as well as providing a protective barrier (film) of relatively cool air flowing around the blade's exterior.
4. *Transpiration Cooling.* Similar to film cooling except that it uses a huge number of tiny cooling holes. A porous blade material allows cooling air to ooze out through the blade's walls, carrying away the heat and then forming the flowing film of cool air around the blade.

The first three of these techniques have seen widespread use for several years. Notable improvements in cooling efficiency continue to be realized, through the implementation of CFD to evaluate the effectiveness of various cooling passage geometries and to understand the heat transfer from the flowstream to the turbine blades. Implementation of transpiration cooling is limited by the availability of porous materials that exhibit the necessary strength characteristics.

[11] An alternative to RIT is the *turbine inlet temperature.* This is the temperature of the combustion products as they enter the first row of stationary turbine blades, upstream of the rotor. This temperature is normally a few degrees hotter than the RIT because cooling air is passed into these stationary blades and then out through their walls to keep them cool (film cooling). When this air mixes with the combustion products, it lowers the temperature of the combustion products slightly, before they enter the rotor. While the temperature entering the vanes is hotter than that entering the rotor, these stationary blades do not have to withstand the high centripetal stresses associated with the turbine rotor's rotation. Therefore, it can be argued that the RIT is a better indication of the turbine's level of technology.



SOURCE: Janos, Benon Z., Massachusetts Institute of Technology, at http://www.mit.edu/people/janos/tbc.htm. Copyright Benon Z. Janos 2000. Reprinted by permission.

Figure 2.5—Materials and Heat Transfer Effects on a Film-Cooled Turbine Blade

engine parts can be safely used. These factors include both steady-state and cyclic effects. Among the steady-state factors are centrifugal stresses on the turbine and compressor rotors' disks and blades that can cause these parts to stretch (resulting in permanent "plastic" deformation) in a process known as *creep*. Exposing these blades to high temperatures weakens the blade materials and accelerates this process. Similarly, small cracks in components can grow in size, eventually leading to component failures. These failures can be catastrophic, especially when the failed components are compressor or turbine rotors. This crack growth and component failure process is known as *stress rupture.*

Cyclic failure is intuitively understood by imagining a piece of metal breaking in two after it is bent back and forth several times. The engine development community classifies most cyclic failures as either *low cycle fatigue* (LCF) or *high cycle fatigue (HCF)*. The dif-

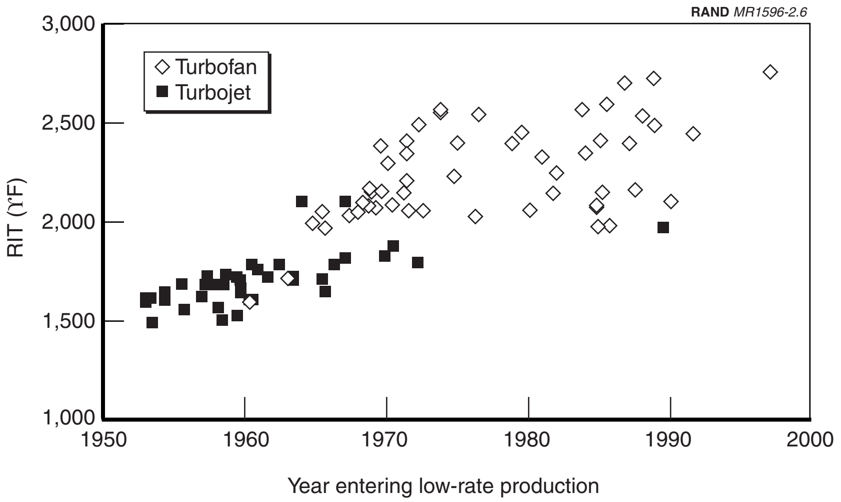


Figure 2.6—Turbojet and Turbofan Rotor Inlet Temperature Trends Since 1950

ference between the two is related to the frequency of the fluctuating forces. Mechanisms that cause LCF include starting and stopping an engine or changing throttle settings, which produce major variations in thermal and mechanical stresses. In contrast, examples of HCF include the small impulses caused when the aerodynamic wakes of rotating turbine blades pass downstream of stationary turbine blades, and when uneven (distorted) flow into the engine inlet causes a fan blade to feel a variation in aerodynamic forces every time it makes a 360 degree rotation.[12]

Understanding that component life is limited in this harsh environment, engine manufacturers must ensure that component designs are robust enough to provide a minimum specified number of safe

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[12] The engine community continues to discover and implement new ways to extend engine life. For example, the Air Force's Engine Structural Integrity Program provided excellent advances in component design techniques to combat low-cycle fatigue problems. Today, the HCF research of the Integrated High Performance Turbine Engine Technology Program (IHPTET), a Department of Defense (DoD) program with Air Force research lab involvement, is working toward a 50 percent reduction in HCF-related failures.

operating hours. Due to the effect of elevated temperatures and operational stresses, the design life of an engine's hot section components is typically shorter (often half as long) than that of its cold section components. Over the history of jet engine development, the design lives of rotating components have increased dramatically. However, as engines operate at higher temperatures and stresses, and new materials are introduced, new failure modes are discovered. These unanticipated failure modes can keep engine components from achieving their design life expectancies.

The high-level parameters we described in this chapter quantitatively capture information that is relevant to engine costs. Another factor that greatly influences development costs, as well as production and operations and support (O&S) costs, is the development approach selected by the engine producer and customer. The following section briefly describes three common development approaches.

APPROACHES TO JET ENGINE DEVELOPMENT

In some cases, when an aircraft is being designed or upgraded, an engine that has already been fully developed for another aircraft (military or civilian) can be adopted directly as an "off-the-shelf" item. While off-the-shelf engines may still require aircraft-specific inlet or nozzle design and integration, and may require military qualification testing, the cost of these engines should be well understood and the costs associated with adapting them should be relatively minor. At the other extreme, developing an aircraft engine from scratch (referred to as a "new centerline" engine) can cost billions of dollars. A common intermediate solution is to develop a "derivative" engine. A derivative development starts with an existing engine and changes components and controls to "derive" an engine that meets the new requirements. In some cases, derivative engines are simply "growth" versions of their predecessors that are intended for use in the same aircraft to accommodate increased mission requirements or to compensate for increasing aircraft weight. In other cases, a derivative engine may be so different from the original engine that its commonality with the original is outwardly indiscernible.

Derivative engines are built around a previously designed engine's core (sometimes these cores are also enhanced over their original design) and may also include other existing components. While engine cores are often a relatively small part of the entire engine, they tend to be expensive to design and build due to their high operating temperatures, the pressures and stresses placed on them, the wide range of operating conditions over which they must function smoothly, and other factors. However, in many cases, significantly different engines have successfully used the same or similar cores.[13] Typically, developing a new centerline engine is more expensive than developing a derivative engine. Furthermore, both the new centerline and derivative approaches are normally much more technically challenging and costly than adapting an off-the-shelf engine or making minor modifications to upgrade an existing design.[14]

SUMMARY

The high-level parameters and development approaches described in this chapter are common throughout the engine community. Their relative importance depends upon the engine's application. For example, while the designer of an expendable (one-time-use) missile engine will probably place a much higher priority on low weight and low cost than on engine life, the designer of a transport aircraft engine will concentrate on providing excellent fuel efficiency and durability, and a fighter engine designer may place the greatest emphasis on thrust and thrust-to-weight ratio, while preserving efficiency, durability, and affordability. The correct combination of engine design approach and engine parameters must be reflected in

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[13] Simply incorporating the design principles and practices used in previous engine development programs does not constitute a derivative development; both new centerline and derivative developments will exploit proven design practices and principles as is appropriate. Similarly, using individual components from other engines does not constitute a derivative engine, in that much of the development effort and cost go into the matching and integration of components (matching rotational speeds and airflow rates, avoiding resonant frequencies, and other specifics).

[14] Typically, small engine modifications and adaptations of off-the-shelf engines would alter a few of the engine's components. These modifications would likely change the cost of engines by a much smaller percentage than a derivative engine development, and possibly the changes are smaller than the magnitude of the margin of error of the CERs being developed through this research. Therefore, estimates of individual component modifications developed through a bottom-up cost-estimating approach will likely provide a better estimate of the cost of the modified new engines than using whole engine CERs.

cost-estimating relationships to get an accurate cost prediction of each of the engine classes included in the scope of the CER.

The engine community also uses parameters to rate the quality and performance of individual components (e.g., the “combustor efficiency” measures the fraction of the injected fuel that is burned.) However, component efficiencies will normally not be used as independent variables in high-level CERs because they are too detailed, and their values are normally not known precisely until the engine design is quite mature. Therefore, these parameters are beyond the scope of this report and will not be discussed further.

Nevertheless, as military requirements and society’s expectations change, new design constraints and corresponding metrics are created. For example, both the society at large and the military have expressed compelling arguments to reduce jet engine smoke, chemical pollutants, and noise, and metrics are now used to quantify noise and emissions levels. Similarly, stealth and thrust-vectoring requirements have led to the development of new engine design constraints and metrics. In addition, rapid progress in sensor and computer processing technologies is providing the opportunity to integrate health monitoring, diagnostic, and prognostic capabilities on jet engines, which will lead to additional durability and reliability metrics.

This phenomenon of new and unrelated factors influencing an engine’s life-cycle costs has implications for engine CERs covering development, production, and operations and support. While these and other new factors could increase or decrease costs, it is nearly impossible to identify every future cost driver when a CER is being developed. However, if the CERs are based only upon the traditional performance metrics, they cannot reflect the influences of new factors on costs. Therefore, the CERs should also have some ability to reflect new design factors generically, without one having to know precisely what these factors are when the CERs are defined. The approach to capturing these design factors and other advances in engine CERs is addressed in Chapter Six.

Chapter Three

TRENDS IN TECHNOLOGICAL INNOVATION

It is impossible to predict precisely when new technologies will be mature enough to be used in weapons systems or to know what future military requirements or economic or social factors will motivate the inclusion of one technology over another in those systems. Nevertheless, several major engine technology development programs currently show promise for both advances in jet engine capabilities and opportunities for life-cycle cost savings over the next 20 years. In this chapter, we discuss several noteworthy jet engine development programs and technological advances.

PROGRAMS AND INITIATIVES

In the early 1980s, it was not uncommon to hear industry observers express the opinion that jet engine technologies had reached a plateau and had little promise for any payoff from additional investment in them. Since then, the industry has designed and produced new military and commercial engines with greatly improved performance, efficiency, and life expectancy, and less environmental impact (i.e., reduced emissions and noise), and many more improvements are now on the drawing board. The United States and the United Kingdom, along with France, Japan, and other countries, have jet engine industries that contribute to strong international competition and technological innovation.

Continued innovation in jet engine technologies is supported through various means. Naturally, company-funded research provides a foundation for technological advances. In the United States in recent years, a key mechanism for engine technology development has been the Integrated High Performance Turbine Engine Technology (IHPTET) program. IHPTET is a joint program of the U.S. Air Force, Navy, Army, Defense Advanced Research Programs Agency (DARPA), National Aeronautics and Space Administration (NASA), and industry (Rolls-Royce's Allison Advanced Development Company [AADC], General Electric Aircraft Engines, Honeywell, Pratt & Whitney, Teledyne Continental Motors, and Williams International). IHPTET is focused on developing technologies for more-affordable, more-robust, and higher-performance turbine engines. IHPTET's long-standing "challenge" to "double propulsion capability" refers to a top-level goal of doubling the thrust-to-weight ratio of fighter engines over the original design of the F119 engine, the most advanced engine in military service.

Because many of the technologies that IHPTET develops have both military and commercial applications, all of the program's participants contribute to the development funding of this program. (See St. Peter [1999, p. 383] for a good overview of the history, goals, and achievements of the IHPTET program since its inception in the 1980s.) IHPTET is scheduled to be completed in 2005 and will be followed by the Versatile Affordable Advanced Turbine Engine (VAATE) Initiative. VAATE's focus will include propulsion capability (thrust-to-weight ratio and SFC) but will also combine those metrics with engine affordability (development, production, and maintenance costs) metrics in a new metric called the Capability/Cost Index (CCI) (Jay and Gahn [2000], pp. 12-16).[1] In addition, the NASA Glenn Research Center, in parallel and in coordination with IHPTET, is sponsoring the Ultra Efficient Engine Technology (UEET) program, which is seeking technical advancements to improve propulsion performance and efficiency and reduce emissions.

The engine development community is also collaborating on a number of initiatives to reduce the cost of engines by improving the materials and manufacturing systems and processes. In 1995, the Air Force implemented the Engine Supplier Base Initiative (ESBI). ESBI's goal is to improve engine affordability through cost avoidance at and between every level of the "supply chain"—government, manufac-

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[1] The details of the CCI metric, as well as the entire VAATE program, were still being finalized as of this writing.

turer, and suppliers (Ormbrek and Wright, 1998). The ESBI effort has focused on the industry involved in investment-casting (a technique used to case metal parts), as investment castings account for 34 percent of the cost of all manufacturing processes associated with a production engine. A primary task of this program has been to improve collaboration among participants, namely, the Air Force Research Laboratory, Rolls-Royce (AADC), General Electric Aircraft Engines, Lockheed-Martin Aeronautical Systems, Pratt & Whitney, Howmet Corporation, and Precision Castparts Corporation. Beyond the organizational goal of improved interbusiness relationships, a "total value chain" sectorwide approach was adopted. This total value chain included electronic data exchange among members of the supply chain, simplified audit procedures, standardization of processing, development of testing methods/specifications, and preparing reports for the user. The organizational changes in the industry have been complemented by a series of technical projects targeted at improving airfoil tolerance and reducing structural rework, reducing scrap from single crystal turbine blades, reducing tooling procurement time, and speeding up new part design/process development time.

While the ESBI program is primarily focused on the cost benefits associated with improved alignment of the total value chain and collaboration among the engine community, another program with the same participants as ESBI, the Metals Affordability Initiative (MAI), is targeting advances in the state-of-the-art of process technology, alloy development, process modeling, and other engine development technologies. And while the ESBI program, along with its forging industry participants, has been specifically targeted at the casting and forging of engine components, the scope of the MAI is broader—it covers metallic components in both the airframe and the engine. The MAI consists of a consortium of raw metal suppliers, processing companies, original equipment manufacturers (OEMs), and military labs. The overall goal of the MAI is a 50 percent reduction in the acquisition cost of metallic parts, while accelerating implementation time for new or redesigned products.

COMPONENT AND RELATED TECHNICAL ADVANCEMENTS

Jet engine technology improvements continue to influence engine life-cycle costs (costs associated with development, production, and operation and support). Enhanced performance naturally comes at the price of increased costs. However, the stated affordability requirements of the Department of Defense (DoD), along with competition from foreign engine manufacturers, are demanding that the industry focus on life-cycle cost reductions. This new focus has resulted in government and industry efforts to reduce engine production costs and enhance engine manufacturability, maintainability, and durability. Efforts to improve many of the traditional jet engine technology areas will continue, including efforts in advanced aerodynamics, component cooling techniques, materials development, and computational modeling and simulation of structural components, flow, and combustion.

Several other technologies are being developed for or are being integrated into major programs for the first time. The following subsections briefly describe several relatively new engine technologies and how they will likely affect costs associated with jet engine performance over the next several years. This list of technologies, while not intended to be comprehensive, highlights many key technologies that program managers and cost analysts are likely to encounter over the next two decades when examining options for military aircraft engines.

Low Observables

The Air Force has demonstrated clear advantages in operating combat aircraft without being detected. An aircraft engine, without the proper precautions, can produce observable "signatures" including strong radar returns, infrared emissions, noise, and visual signatures. The engine production community has developed techniques for partial suppression of these signatures (i.e., low observability) and will continue to explore new approaches in this area. In general, incorporating techniques to create low observable (LO) aircraft adds cost throughout the engine's life cycle. For example, developing and producing LO components requires special materials and shaping of the aircraft, maintaining LO components requires special handling and treatment, and some approaches to LO design cause slight increases in aircraft weight and fuel usage. Because much of the technology related to achieve low observability is varied, proprietary, and/or classified, little cost-estimating information is publicly available. Therefore, although LO technology is already in use on a number of military aircraft, estimators must rely on either cost information supplied by individual development programs (and those costs are also closely protected) or costs derived from activity-based or materials-based modeling.

Integrally Bladed Rotors

Integrally bladed rotors (IBRs), also called bladed disks or blisks, are one-piece units that make up the rotating portion of a fan or compressor stage of a jet engine. IBRs consist of several blades (airfoils) attached to a rotor that holds the blades in position and is attached to the other compressor/fan rotors and shaft in the engine. An IBR can be manufactured as a single part or the blades can be welded to the rotor during manufacturing. Currently, fan blades that are hollow for reduced weight are welded onto the rotor. IBRs are quickly becoming the norm in newly developed fans and compressors.

IBRs reduce the engine's part count, weight, and aerodynamic losses, and eliminate each rotor blade's traditional "dovetail" attachment

RAND *MR1596-3.1*

Figure 3.1—Integrally Bladed Rotor (Blisk)

roots. The elimination of this dovetail attachment, in turn, eliminates the problem of crack initiation and subsequent crack propagation at the point where the blades and rotors attach. The lower aspect ratios of modern fan blades (resulting in blades that resemble heavy meat cleavers rather than long carving knives) should provide greater tolerance to foreign object damage (FOD) and "bird strike." However, if IBR blades are damaged, their repair may be more difficult because the blades cannot be replaced on the flightline (airports, aircraft carriers, air bases, and other places of operation). Although "on-wing blending" (filing a fan blade's damaged leading edge, within tolerable limits, without removing the engine from the aircraft) may be an acceptable repair technique for some minor dents, more serious damage will likely result in the engine having to be removed, and entire IBRs will need to be replaced or replacement blades welded on.

Because the blades on the IBR disk are manufactured quite uniformly, they all have very similar harmonic frequencies and, therefore, do not have the benefit of the vibration damping provided by the traditional blades' dovetail attachment mechanisms. Therefore, IBRs must be very carefully designed and tested to ensure that catastrophic "tuning fork–like" harmonic vibrations do not occur in the fan or compressor.

Alternatives to Engine Lubrication Systems: Air Bearings or Magnetic Bearings

The lubrication system on a typical jet engine provides oil to the main bearings that support the engine's "spools" (a spool consists of a turbine and a compressor or fan, and the shaft that connects the two). These main bearings withstand extremely high forces, especially during tactical maneuvers.[2] The engine's lubrication system also provides oil to the power-takeoff assembly that drives the fuel pump, alternator, and the oil pump itself.

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[2] Not only does a high–gravitational force maneuver multiply the effective weight of the spool, but pitching or yawing of the aircraft creates enormous gyroscopic forces on the spool, similar to the feeling one would experience when holding a spinning bicycle wheel's axle and rocking it side to side.

This lubrication system is a source of vulnerability for the engine. Specifically, if the lubrication system fails through use or due to battle damage, the engine must be shut down and may be destroyed by the loss of lubrication before it can be shut down. Even if the engine is safely shut down, the aircraft may not be able to return to a runway to land safely. The lubrication system also generates costs throughout the engine's life cycle. Clearly, costs are incurred in designing, integrating, and producing this subsystem. In addition, the quality of the oil operating in the hot engine environment must be monitored and maintained, leaks must be stopped, and worn or damaged components must be repaired or replaced. The oil's maximum allowable operating temperature limits the bearing's allowable operating temperature and increases the engine's cooling requirements. Finally, the lubrication system, including the sump, pump, tubes, oil, and other components, adds weight to the engine.

The engine production community is exploring alternatives to lubrication systems. Because no one has invented a reasonable alternative to rotating compressors and turbines for jet engines, some form of bearings will continue to be required. Two oil-free bearing systems are under consideration. Foil air bearings would cause the spools' shafts to ride on films of high-pressure air. Today, foil air bearings are used in aircraft environmental control systems (Agrawal, 1998). Alternately, *magnetic bearings* could levitate the spools. Due to the extreme loads the bearings must support in jet engines, both air bearings and magnetic bearings require further development. Initially, either type may be integrated in a hybrid fashion that also includes conventional bearings (with a greatly simplified lubrication system) to provide bearing augmentation at high gravitational forces.

Thrust-Vectoring Nozzles for High-Performance Tactical Aircraft

Thrust vectoring (turning the engine's exhaust to change the direction of the thrust force) enables exceptional aircraft maneuvering and reduces the need for large aerodynamic control surfaces (e.g., a horizontal tail) on the aircraft. The F-22 uses large, two-dimensional rectangular cross-section nozzles to vector thrust upward and downward. However, these large thrust-vectoring nozzles, with their thousands of moving parts, are expensive and challenging to design due to the extraordinary forces, temperatures, acoustic vibrations, and other elements to which the nozzles are exposed and the limited "signatures" that they are allowed to produce. Although several design approaches have been explored in the laboratory and on experimental flight-test aircraft, the F-22's F119-100 engine will have the first production thrust-vectoring nozzle. The Air Force and Pratt & Whitney have worked hard to control the cost and complexity of these nozzles. However, there is still opportunity to enhance affordability, maintainability, and simplicity in future-generation mechanical thrust-vectoring nozzles.

Fluidic Nozzles for Afterburning Thrust-Vectoring Engines

Fixed-geometry *fluidic nozzles* are an attractive alternative to mechanical thrust-vectoring nozzles. These devices would selectively inject small jets of air or sheets of high-pressure air (bled from the compressor) into the nozzle's main flow stream to change the nozzle's flow area and direct the thrust as needed. Because fluidic nozzles would not have any moving parts in direct contact with the hot exhaust jet, they should eventually be much cheaper to design, produce, and maintain. However, this challenging technology is in its formative stages and will likely take several years to mature.

Integral Starter-Generators and Electric Actuators

Alternators on an aircraft's main engines produce the majority of the electrical power for the engine's controls and for the aircraft's avionics, lighting, and other systems.[3] These alternators are an integral part of the power-takeoff assembly, which is driven by a power-takeoff shaft geared to the engine's low- or high-pressure spool. This power-takeoff assembly adds to the engine's weight, complexity, part count, and requirements for lubrication. The engine community is designing alternators that will be manufactured as an integral part of one of the engine's spools.

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[3] Electrical power is also provided by the aircraft's auxiliary power unit (APU) and batteries. When the aircraft is on the ground and the engines are not operating, the aircraft's APU, batteries, and/or a separate ground power source provide all the aircraft's electrical power.

Once integral starter-generator (ISG) technology is mature, it should reduce both cost and weight and increase reliability by eliminating the engine's power-takeoff assembly. The engine's oil, fuel and hydraulic pumps can be electrically driven and the hydraulics systems can be eliminated completely if the engine's and the aircraft's actuators are converted to electrical devices. Furthermore, if the bearings are replaced by the foil air bearings or magnetic bearings described earlier, the lubrication system can be eliminated or greatly simplified and miniaturized. While this ISG technology is less risky than magnetic or air bearings and fluidic nozzles, it is still several years away from being fielded.

Prognostics and Engine Health Management

Advanced engine health monitoring systems, including prognostics and diagnostics, along with electronic technical manuals, should reduce the total labor required to maintain engines and allow maintenance crews to plan for and accomplish preventative maintenance more effectively.

The concept of monitoring engine performance has been around as long as engines themselves. However, the large advances in computing power, rugged and miniaturized sensors, artificial neural networks (ANNs),[4] and diagnostic and prognostic algorithms will permit the incorporation of intelligent and responsive health assessment systems to improve engine reliability, predict degradation or failure, and prescribe corrective actions. The system will notify the pilot of near-term problems and inform the ground crew of required maintenance. At the end of each flight, engine behavioral characteristics will be downloaded to a central database. In addition to managing engine health, prognostic algorithms that track trends in engine

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[4] ANNs are based on the construct of biological neural networks and as such are able to learn, remember, and associate new information with learned information. Like their more complicated biological counterparts, these systems are collections of individual, but interconnected, neurons. ANNs are trained to provide appropriate responses to stimuli by adjusting the individual neuron's positively or negatively weighted responses to input from each other. Klerfors (1998) provides a more detailed tutorial on ANNs and their potential applications, pointing out that the most successful applications of artificial neural networks are in categorization and pattern recognition.

status and predict future problem behavior (such as compressor stalls, loss of efficiency, increased emissions, component wear and failure, and other behaviors) may be accompanied by control algorithms that can adjust engine settings in flight to reoptimize performance. These capabilities should save O&S funds or at least allow O&S costs to be predicted more accurately and budgeted. However, these capabilities will add to development costs until this technology field fully matures and is integrated into engines.

Advanced Fuels

Advancements in fuels for jet engines have been primarily in the form of new additives and improved refining processes to enhance the safety, operability, and maintainability of engines, rather than to increase the energy level of the fuels.[5] The practice of using an aircraft's fuel as a heat sink to cool avionics and other components has caused the fuels to approach their thermal limits as these heat loads have increased.

Heating a fuel past its thermal limit causes it to begin to decompose, leaving a residue called *coke* that can clog the fuel lines and injectors. The Air Force Research Laboratory (AFRL) has developed a new fuel, JP8+100, which incorporates an additive that increases by 100°F the temperature that the fuel can reach without coking. As an added benefit, AFRL has discovered during operational field testing that this additive actually cleans the engine parts downstream of the combustion process. This additive increases the cost of the fuel by approximately one cent per gallon. AFRL continues to work on fuels that can withstand even higher heat loads. As these fuels are introduced, they may significantly affect O&S costs as costs of fuel, engine maintenance, spare parts, and other costs change.

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[5] To obtain significantly greater fuel energy densities (fuel heating values), a significantly different fuel must be used. The liquid hydrocarbon fuels derived from crude oil (e.g., jet propellant–type fuels, gasoline, and kerosene) all have similar fuel heating values. Less complex hydrocarbon fuels (e.g., methane [CH_4]) typically have somewhat higher heating values, and hydrogen's heating value is more than twice that of traditional hydrocarbon fuels.

Cooled Cooling Air

As the maximum combustion temperatures in engines increase, the hot sections of the engine require new high-temperature materials, greater cooling by air bled from the high-pressure compressor, and more-effective cooling schemes. Bleeding more compressed air to cool components is not an ideal solution because this decreases the engine's thermodynamic efficiency by removing air (which has already been compressed) from the combustion process. One way to reduce the amount of cooling air that is required is to use cooled cooling air (CCA). However, the cooling air must be at a higher pressure than the combustion products flowing through the turbine, and because compressing the air also increases its temperature, the temperature of the bled air exiting the compressor increases with the OPR. In today's engines, this "cooling" air can be well over 1,000°F.

Therefore, by adding a heat exchanger to the engine that transfers energy from this very warm "cooling" air to the fuel, a smaller amount of cooling air would be needed. If this type of heat exchanger is added to future engines, it should improve the overall efficiency of those engines by extracting less cooling air, permitting higher performance (thrust-to-weight ratio) through higher RITs or providing better life expectancy for engine parts. However, the heat exchanger will add to the engine's complexity, part count, weight, and vulnerability to being detected, and it will add to the heat load on the aircraft's fuel.[6] Thus, cooling the cooling air will affect development, production, and O&S costs.

Advanced Materials

The selection of materials for jet engines plays a primary role in determining the performance, weight, life, and costs of these systems. Early engines were mostly made of steel. Today's engines are made of a variety of materials, including high-temperature nickel-based superalloys, titanium, aluminum, steel, composites, and ceramics.

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[6] Friction between the cooling air and the heat exchanger's internal air passages will reduce the pressure of the cooling air slightly, which may lead to some of the cooling air needing to be in a small auxiliary compressor, further adding to the engine's part count and complexity.

Although a detailed discussion of these materials and candidate advanced materials is beyond the scope of this report, a brief description of two classes of candidate materials and their development issues and cost implications appears next.

Ceramics and Ceramic Matrix Composites

The engine community is investigating the potential for greater use of ceramics for hot engine parts. These materials can withstand temperatures over 2000°F without cooling and could provide substantial weight savings compared with conventional metallic alloys. However, ceramics are more brittle than metals, precluding their use to date as structural elements in turbines (where the combination of high temperatures and material stresses are greatest) and in most other safety-related engine components. In addition, joining ceramic and metal parts without damaging the ceramics is difficult, and the difference in rates of thermal expansion further complicates their integration.

Much of the ongoing ceramics research involves attempting to increase the structural durability of ceramics without compromising their high-temperature stability. In this respect, fiber-reinforced and particulate-reinforced ceramic matrix composites (CMCs) are being designed to reduce brittleness by introducing internal barriers (such as steel reinforcing bars used in concrete structures or roads) to the propagation of cracks. However, to date, even these techniques do not provide levels of fracture toughness that are comparable to those of metals. Nevertheless, CMCs are being used to some degree in low- to moderate-load components of the engine (nozzles, combustors, and other such components) (Flower, 1995). Considerable effort continues in ceramics research, and the IHPTET program is testing ceramic bearings, turbine blades, and other components (Jay and Gahn, 2000, pp. 7 and 11).

Intermetallics

Another class of developing materials, *intermetallic alloys*—including titanium aluminides, nickel aluminides, and niobium intermetallic composites—offer strength, temperature endurance, and weight advantages over current materials. Titanium aluminides are useful at temperatures higher than temperatures at which aluminum can be used and offer substantial weight savings over pure titanium or nickel-based alloys, making them good candidates for combustor cases, compressor blades in the last (highest pressure and temperature) stages, and other such applications. Similarly, nickel aluminides and niobium intermetallics exhibit higher temperature capabilities than do nickel-based superalloys, making them good candidates for future turbine airfoils (St. Peter, 1999, p. 415). However, these materials' properties (e.g., ductility) are still being assessed and manufacturing processes are still being refined. Continued research and development will likely solve any remaining issues, and intermetallics should enjoy an increasing presence in future engines.

SUMMARY

Jet engine design, production, operation, and support are complex activities. The design of safe, affordable, and reliable jet engines requires the integration of many technical disciplines, including aerodynamics, thermodynamics, fluid mechanics, solid mechanics, materials development, fuels research, combustion systems design, heat transfer analysis, and controls development. The resulting jet engines are complex devices that test the finite capabilities of each of these technical disciplines. Additionally, the operation and support of these engines and the aircraft they power require various professional skills, including skills in propulsion systems usage, maintenance, contracting, supply management, and many other areas.

This chapter provided basic information on how jet engines work, the parameters used to compare the performance of different jet engines, development process alternatives, and likely future trends in jet engine technologies. This information will help program managers and cost analysts to employ the cost-estimating relationships described later in this report and should facilitate discussions about jet engines and the related factors that influence the costs associated with them.

PART II: DATA ANALYSIS AND COST-ESTIMATING TECHNIQUES

Chapter Four

AN OVERVIEW OF COST-ESTIMATING METHODS

Estimating future costs and development schedules is one of the most difficult tasks that analysts face. There are three basic methods to conceptual cost estimation: *bottom-up, estimate by analogy,* and *parametric* approach (Fisher, 1974, p. 75). This chapter provides an overview of the three main methods used in estimating turbofan engine costs. We discuss the details of each methodology along with their advantages and disadvantages.

BOTTOM-UP METHOD

The bottom-up approach relies on detailed engineering analysis and calculation to determine an estimate. To apply this approach to aircraft engine production costs, an analyst would need the detailed design and configuration information for various engine components and accounting information for all material, equipment, and labor. A conceptual engine design is built from scratch (hence the name “bottom-up”). This approach generates a fairly detailed forecast. One of the advantages of this approach is that many issues can be addressed, and the effect of each issue can be well understood. For example, we could isolate the effect of choosing a new material in construction or a new manufacturing method. All of the representatives from engine producing companies whom we interviewed during the course of this study indicated that they employ some form of this bottom-up approach to estimating aircraft engine costs.

However, the bottom-up method has some drawbacks. First, the analysis process is time consuming. Often, a great deal of time must be spent generating the conceptual design and corresponding cost estimate. Some companies have automated the process by creating sophisticated database tools, but these systems can be quite expensive to develop. A second drawback of the bottom-up approach is that the analyst must be an expert in the design of the technology being employed. Specific design details must be considered to apply the method correctly. The user (i.e., cost estimator) must also understand design tradeoffs and the current state of technology. A third disadvantage is that the system must be well defined—there is little allowance for unknown factors. For example, a component's cost must be estimated even though that component might represent a first-of-a-kind technology. Finally, the user of the bottom-up approach must have access to, or maintain an extensive and detailed database of, development, production, and operating and support costs for the particular technology.

ESTIMATING BY ANALOGY

A related approach to the bottom-up method is to estimate by analogy. With this approach, an analyst selects a system that is similar to or related to the system undergoing the cost analysis and makes adjustments for the differences between the two systems. This approach works well for derivative or evolutionary improvements. Its main advantage over the bottom-up approach is that only the changes or differences must be estimated—thus saving time. However, a good starting baseline must exist to apply the method successfully. For radical changes or new technologies, the bottom-up approach is clearly the better choice. As with the bottom-up approach, the analyst must have a thorough knowledge of the applicable technology to employ the estimate by analogy approach.

ESTIMATING BY PARAMETRIC METHOD

A third approach that is quite different from the first two uses parametric methods to forecast outcomes. Parametric methods are based on a statistical technique that attempts to explain the dependent variable (e.g., cost, development schedule) as a function of several other variables, such as intrinsic engine characteristics (e.g., size, technical characteristics, features, risk measures), which are the independent (or explanatory) variables. The relationships between these variables are frequently determined using a statistical technique, such as ordinary least-squares (OLS) regression.

The parametric relationships used for estimating costs are CERs. OLS can be applied to functional forms that are linear combinations of the explanatory variables. The functional form most often used in parametric methods is the “double log” or “log-log” form.[1] The format of a parametric relationship is

$$\ln Y = \beta_o + \sum_i \beta_i \ln X_i + \varepsilon$$

where β_0 and β_i are coefficients, X_i are parameters (i.e., independent variables), and Y is the outcome or the dependent variable. This form is based on the assertion that errors are normally distributed in log space and not in real space. Using least-squares regression requires the residuals to be normally distributed with constant variance. A log-log relationship implies that our uncertainty in a predicted value is relative and not absolute. In other words, a forecast would be plus or minus a percentage value (rather than plus or minus some fixed dollar value) so that the error scales with the magnitude of the forecast.

Parametric analysis has some strong advantages for estimating costs and the duration of development schedules. Its principal advantage is that after the basic parametric estimating relationship has been defined, applying the method is straightforward. Further, the analyst is not required to be a technical expert; however, to apply the method, the analyst must obtain values for all input parameters. Unlike the previous two approaches, a detailed conceptual design is not necessary to employ this method. Another, more subtle, advantage of parametric relationships generated using OLS regression is that one can also generate information on uncertainty of the forecasted value. In other words, one can obtain a result of $y \pm \varepsilon$ where ε is related to the error terms of the regression. This uncertainty value can be just as informative as the predicted value.

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[1] The double log form is the most commonly used functional form that is nonlinear in the variable while still being linear in the coefficients.

Although the parametric method is easy to use, developing parametric relationships can be difficult. Despite the existence of well-defined methods and systems using OLS, the development process in parametric analysis is somewhat of an art. First, one needs to define the appropriate estimating parameters. This step is most critical in the development of parametric estimating relationships. How the parameters are determined often defines the ultimate usefulness of the relationship between variables. Next, the analyst must gather data (observations). Finally, those data then must be normalized and adjusted to a common basis.

Another disadvantage of the parametric method is the lack of direct cause-and-effect relationships. Parametric equations developed through OLS only show *associative* influences of the dependent variable to the independent variables. For example, imagine that *rotor inlet temperature* is a term in a parametric relationship for *unit production cost* (having a positive coefficient). What might drive such a relationship? The regression results show only that higher production costs are correlated with higher inlet temperatures. The root cause could be something subtler. One possible explanation for the higher production costs is that higher inlet temperatures require more-expensive construction materials. On the other hand, the turbine blade materials, for example, could be difficult to machine and thus require more production hours, or have a higher scrap rate. Another possibility is that additional equipment or greater part size is necessary to cool the engine effectively. Alternatively, a more complex (and expensive) combustor may be required for operating the engine. A bottom-up approach would have to consider all these possible factors and could directly show the contribution of each factor. The parametric relationship does not address these causative factors.

Parametric relationships are based on the correlation between historical data on independent parameters and on the cost of developing and producing engines. Any forecast derived from using this method assumes that all the relationships inherent to the future engine being estimated still apply. So, extrapolation from using CERs based on historical data to forecast future costs of engines with a major technical improvement is perilous. Often, analysts may be unaware that they are pushing a parametric relationship beyond the reasonable limits of the historical data.

SUMMARY

Table 4.1 summarizes the advantages and disadvantages of each approach. For this study on aircraft engine costs and schedules, we employed the parametric approach for several reasons. We have neither the expertise nor the detailed data to develop cost estimates using the other two methods. And, even if we did, we have no means to convey the information because it is in a format that cannot be easily translated to this report. Further, several other researchers have successfully used the parametric approach to derive estimating relationships for aircraft engine costs; therefore, we had a foundation upon which to build our estimates.[2]

Table 4.1

Advantages and Disadvantages of the Three Conceptual Estimating Methods

Approach	Advantages	Disadvantages
Bottom-up	Cause and effect understood Very detailed estimate	Difficult to develop and implement Substantial, detailed data are required Requires expert knowledge
Estimate by Analogy	Cause and effect understood More easily applied than the bottom-up method	Appropriate baseline must exist Substantial, detailed data are required Requires expert knowledge
Parametric	Easiest to implement Nontechnical experts can apply method Uncertainty of the forecast is generated	Can be difficult to develop Factors might be associative but not causative (i.e., lack of direct cause-and-effect relationships) Extrapolation of existing data to forecast the future, which might include radical technological changes, might not be properly forecast

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[2] Watts (1965); Large (1970); Anderson and Nelson (1972); Nelson and Timson (1974); Nelson (1977); Nelson et al. (1979); Birkler, Garfinkle, and Marks (1982); and Cote and Lilly (1985).

Chapter Five

ESTIMATING PARAMETERS AND GATHERING DATA

The principal focus of our work in this study is to add new observations on estimating aircraft engine costs to previous RAND studies and update the parametric relationships for engine costs and development time (see Chapter Four for a discussion of parametric relationships). Our goal was to extend and improve the earlier analyses in two ways.

First, most of the previous engine cost studies grouped turbojet and turbofan engine types into the same population. This grouping was done for pragmatic reasons because there were far fewer observations for turbofans than there are today. To provide a more homogeneous population, we focus exclusively on parametric relationships for turbofan engines (as mentioned earlier, turbojet engines are seldom used in modern aircraft for reasons related to efficiency and operating costs).

Second, it was often difficult to determine how the earlier studies treated an engine family. Engines are developed and produced within “families” in which a main engine is developed first and derivative engines follow later. Derivative engines represent either evolutionary improvements to the primary engine or modifications to meet a specific application. Within a family, “dash numbers” identify different engine models. For example, the F100 engine was first produced as the F100–100, with the F100-200, F100-220, F100-229, and F100-232 models following later. In our analysis, we treat each model (or dash number) as a separate observation. However, we explicitly consider how derivative engines relate to first-of-a-kind engines. The resulting equations from that analysis are presented in Chapter Six.

ESTIMATING PARAMETERS

Many parameters may be considered when developing parametric relationships for aircraft engines. We have categorized the parameters into three main areas: performance and physical, technical risk and design maturity, and programmatic.

Performance and Physical Parameters

Performance and physical parameters (discussed in Chapter Two) are measures of technical capability. Factors such as thrust, weight, and specific fuel consumption fall into this category. This category can be further divided into parameters that are *scale dependent* and *independent.* For example, weight and thrust will generally increase as the engine becomes larger; therefore, these parameters are scale dependent. Other performance terms do not necessarily scale with size, such as the rotor inlet temperature or bypass ratio. Parameters such as these are scale independent.

Technical Risk and Design Maturity Parameters

The second general category of parameters includes measures of technical risk and design maturity. These measures quantify the relative difficulty of developing and producing a particular engine. For example, an aircraft engine employing a new technology would be more difficult to develop than one using proven technology. Technical risk and maturity scales in this case are difficult to develop and implement or may not even lend themselves to subjectivity.

An example of a simple technical measure is the year a system is developed. Over time, systems might become less risky to develop as a technology matures. In other words, there is less chance of a significant cost growth or schedule overruns.

More-sophisticated measures of technical risk explain the trends for many factors. An example of such a measure is the delta time of arrival (delta TOA) measure used in earlier RAND aircraft engine studies. Delta TOA is the difference between the predicted model qualification test (MQT) date and the actual MQT date. This measure assumes that technological trends or improvements are monotonic with time and can be measured by technical characteristics of an engine. Thus, a predicted TOA can be generated through parametric analysis of technical characteristics. A positive delta TOA would imply an advanced development—an engine beating the overall development trend. Conversely, a negative delta TOA implies an engine that lags the overall technology development trend.

We attempted to recreate the delta TOA technical risk metric from previous RAND studies. However, when we tried to reestimate the relationship for TOA using the original formulation used in those studies, we found that certain independent parameters were highly correlated with one another—namely pressure was correlated with rotor inlet temperature and thrust was correlated with weight. Also, the parameters for thrust and specific fuel consumption were not significant. We revised the parametric relationship (the mathematical regression model we discuss in detail in Chapter 6) based on the new data. The main parameters we then included were dry weight and rotor inlet temperature. Details of this analysis can be found in Appendix A.

A measure of risk related to the delta TOA is the state-of-the-art (SOA) metric (Greer, 1989). Whereas delta TOA focuses on the trend of technological advancement over time for the overall population of aircraft engines, the SOA measure does not focus on the overall trend but rather concentrates on the trend in the best-demonstrated performance. This approach is an attempt to measure how the cutting edge of engine development evolves. Dividing the actual performance of an engine at a given time by the best performance of an engine at that given time defines the metric. The smaller the number, the further from the state-of-the-art an engine is.

Figure 5.1 shows an example of the SOA metric for turbine engine rotor inlet temperature as a function of the approval date for low-production rate (LPR).[1] The best (highest) points at a given time are

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[1] Soon after the development of an engine is complete, the engine is produced in small quantities (low-production rate) before ramping up to full production (using maximum production capacity).

fit to a third-order polynomial spline[2] versus time. The spline fit defines the SOA at a given time. An SOA index is created by dividing a particular engine's actual value by the SOA value at the time the engine reaches LPR. A higher index value indicates a more technically challenging development. Notice that the SOA curve in Figures 5.1 and 5.2 follow a notional trend for a maturing technology. We also developed state-of-the-art metrics for fan engines using thrust-to-weight ratios. Figure 5.2 shows the SOA curve for thrust-to-weight ratios as a function of LPR date.

A technical risk measure need not be time based. An analyst can employ other factors that quantify the level of maturity. The NASA technology readiness level (TRL) is one such measure that is not necessarily time based (Mankins, 1995). The TRL measure is geared toward maturity of a technology; in other words, it categorizes the extent of development. The TRL scale of levels is shown in Table 5.1.

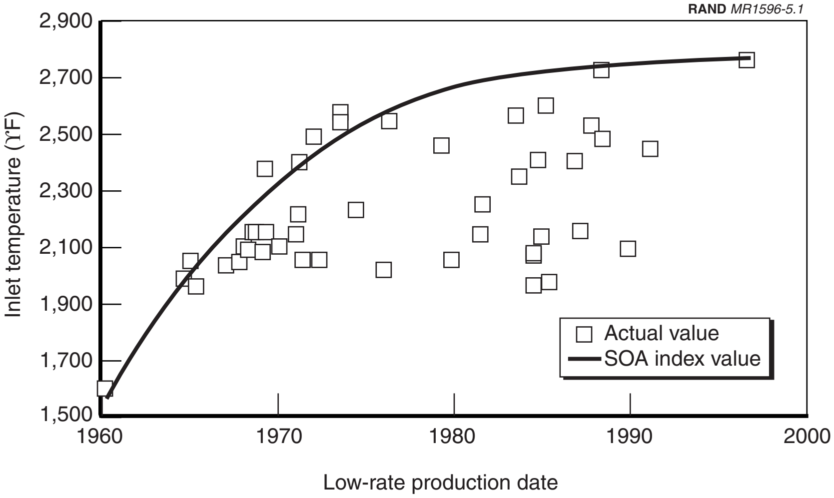

Figure 5.1—State-of-the-Art Metric for Fan Engine Rotor Inlet Temperature

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[2] Readers interested in learning more about third-order polynomial splines should see Sasieni (1994 and 1995).

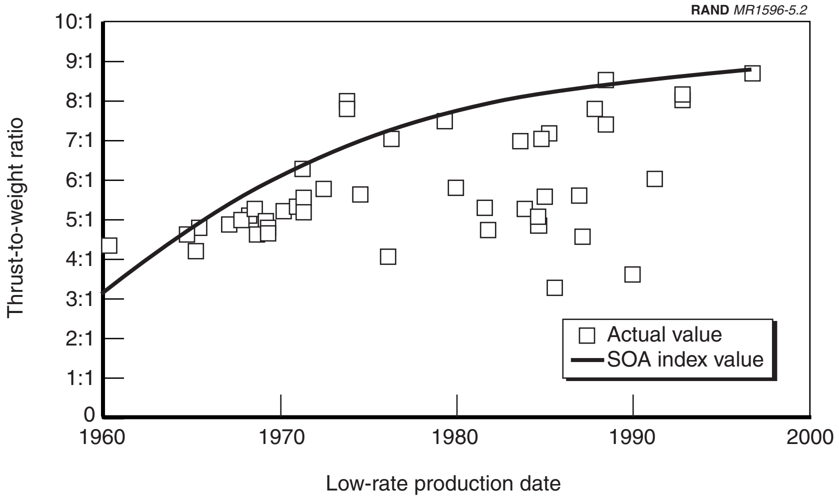

Figure 5.2—State-of-the-Art Metric for Thrust-to-Weight Ratios

Table 5.1

Technology Readiness Levels

Level	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or "breadboard validation" (concept demonstration hardware) in laboratory
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in relevant environment
TRL 7	System prototype demonstration in flight/space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration
TRL 9	Actual system flight proven

Some final examples of technological factors are change scales that center on the degree of change from a baseline. These scales can be either categorical or quantitative. An example of a *quantitative change scale* is the percentage of new design or percentage of new components as compared with the original design. An example of a *categorical change scale* for aircraft engines is presented in Table 5.2. The scale in the table, developed by NAVAIR, rates the various types of changes done to an aircraft engine by the engine producers. As with the TRL scale, technological difficulty notionally increases with the categorical change scale. Each engine that NAVAIR included in its cost database provided to us as part of this study was rated according to this scale.

Additional Measures of Technical Risk and Maturity

To supplement the technical risk and design maturity measures, we examined several additional parameters that fell within the following four categories:

Advanced Technology Engine Developments. Some engines incorporate advanced materials and technologies. The maturity of these new materials and technologies influences development costs. In

Table 5.2

NAVAIR Technical Change Scale for Aircraft Engines

Category	Type of Modification
1.0	Derate (reduction in preformance) (example: F405-RR-400)
1.1	Modification
1.2	Duty cycle change
1.3	Demonstrator program
2.0	Small uprate (<5%)
2.1	Modest uprate(<10%)
3.0	Cold section redesign
3.1	Gearbox addition
3.2	Fan addition to core (example: TF34-2)
4.0	Hot section redesign
4.1	Afterburner addition to dry engine
5.0	Minor overall redesign (example: F404 II)
5.1	Core scale up/down (example: F101DFE)
6.0	Derivative (same engine type)
6.1	Major component redesign
7.0	Derivative (different engine type)
7.1	Major overall redesign
8.0	New engine with demonstration (F100)
8.1	New engine w/o demonstration (J93)
9.0	New design in new class (example: PW100, PW2037)

addition, advancing the technology at the integrated component level by designing new engine types (variations to the Brayton cycle discussed in Chapter Two) to incorporate new modes of engine operation or entirely new methods of carrying out the functions of engine components could affect development costs.

Past and ongoing examples of major technology and cycle changes include shifting from turbojets to turbofans, incorporating thrust vectoring nozzles (such as those in the F119), and incorporating variable cycle capabilities (such as in the F120). Similarly, examples of potential major technical advancements include the shift to fixed-geometry fluidic nozzles for afterburning thrust-vectoring engines and magnetic bearings and integral starter-generators for all new engines.

To explore the influence of advanced technology on development programs, we created a binary variable to indicate whether an engine incorporates advanced technology. The fan engines that incorporate advanced technology, which are included in the sample, are TF30P-3, TF39A-1, F100-100, F100-229, F101-100, F119-100, F120-100, F402 (Pegasus 6), F404-400, and F414-400.[3]

New Centerline Engine Developments. As noted in Chapter Two, engines can be developed as "new centerlines," meaning that they are designed from scratch or designed using a "clean sheet." By contrast, aircraft development programs frequently integrate existing (off-the-shelf) engines or include the development of derivatives of existing engines. Using off-the-shelf or derivative engines normally saves development cost and time and reduces risk when compared with a new centerline development.

Although designing a new centerline for a large engine can cost billions of dollars, it offers the greatest flexibility of design. For example, the designer can optimize the engine's thermodynamic cycle parameters for the aircraft and its intended mission, or sometimes a new engine is designed to fill a requirement for a new thrust class. In

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[3] The decision to designate an engine an "advanced technology engine" is fairly subjective. In some cases, new technologies are incorporated, but they are few in number and do not add significantly to the cost, schedule, and performance risks inherent in a development program.

addition, the designer can also incorporate an optimal combination of new technologies without compromising their contribution to the end product by having to adapt them to constraints imposed by an existing engine core.

To assess the most challenging developments (i.e., new centerline engines), we created a binary flag.[4] The turbofan engines in our sample with new centerlines are TF30P-3, TF30P-8, TF39A-1, F100PW-100, F101GE-100, F109GA-100, F119PW-100, F120GE-100, and F404GE-400.

Series Order in a Family of Engines. To represent the efficiency of the development process for derivative engines, we adapted an analytical technique from production cost analysis. In production, a common observation is that productivity improves as the workforce gains experience producing an item. This observation is the so-called *cost improvement effect.* The cost is typically related to the number of the unit in the production run. Therefore, we sought to develop an analogous measure for engine development.

Such an index is relatively straightforward; it is based on the series order within a family. Within each engine family (e.g., TF34), a series of dash numbers/variants can be produced (e.g., TF34-2 and TF34-100). Based on the contract award date, every variant within an engine family is ordered sequentially and numbered according to that sequence. Engines with identical contract award dates receive the same number. For the TF34 example, TF34-2 would have a series order of 1 (first in the series) and TF34-100 would have a series order of 2 (second in the series).

Programmatic Parameters. The final set of general parameters includes measures that account for programmatic issues. These factors address issues related to the way in which programs are operated. Factors that fall into this category include changes in the engine design, management turnover, the particular service (Air Force or Navy), testing requirements, and other factors. For example, service

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[4] A binary flag (1 or 0), or dummy variable, is a statistical method used to distinguish programs with specific characteristics versus programs without the characteristics. Here, all the engines that were assessed as new centerline developments were coded with a 1 and the remainder of the engines were coded with a 0.

requirements might make the development of the same engine more difficult for one service than for another. A program with many design changes would also be more expensive to develop than one with fewer changes.

Criteria for Including Parameters

Ideally, we would like to include parameters from all three groups—performance and physical, technical risk and design maturity, and programmatic—in developing parametric relationships for aircraft engines. However, there are some limitations to including every parameter. First, we must have all the relevant data for any parameter we wish to include in developing a parametric relationship (more details on data are covered in the next section). Another major consideration is that the parameter must make sense—i.e., a rationale must exist for why a particular parameter correlates with the dependent variable. This rationale should be straightforward. The parameter must also be valid from a statistical standpoint. We will apply the following statistical criteria to parameters (independent variables) presented later in the report:

- The use of a parameter does not exclude many of the observations in the data sample because of missing information.
- The mathematical sign on the coefficient of the regression model must be consistent with the rationale for the inclusion of the parameter/independent variable.
- The parameter must be significant (the probability that the coefficient is zero must be less than 5 percent), and the significance is not driven by a few leveraging observations.
- The parameter is not highly correlated with any other parameter that is of greater significance.
- The distribution of residuals with respect to the parameter is random and normal with constant variance.

Now that we have covered the criteria for the use of parameters, we turn to data collection and the normalization process.

DATA GATHERING

Gathering data is one of the major activities of any statistical analysis. We were fortunate that NAVAIR's Cost Department has maintained a database of aircraft engine production and development costs. These data formed the basis for our analysis. The following list summarizes the fields for the basic information, performance, technical risk, programmatic, and production costs parameters in the engine database we developed for our study.

Basic Information

- Engine model designation
- Aircraft
- Military service
- Afterburning engine (yes or no)

Performance

- Maximum thrust with afterburner, sea-level standard
- Thrust at intermediate rating point (IRP), sea-level standard
- Specific fuel consumption at IRP, sea-level standard
- Air flow rate at IRP, sea-level standard
- Overall pressure ratio at IRP, sea-level standard
- Rotor inlet temperature (maximum rated)
- Dry weight
- Thrust-to-weight ratio (based on maximum thrust including afterburner)
- Hours of hot section life
- Hours of cold section life

Technical Risk

- Technical change scale (see Table 5.2)

Programmatic

- Contractor name
- Full-scale test hours
- Date of technical demonstration
- Date of contract award for engineering development
- Preliminary flight release
- Low-rate production release date (or MQT date, depending on time frame)
- High-rate production release date

Production Costs (by Lot)

- Model
- Year
- Quantity
- Unit cost

Extent of Data

Not surprisingly, our engine database does not have values in every field (i.e., for every parameter). Therefore, a subset of the total database is used for each CER discussed in Chapter Six. Table 5.3 summarizes information on the fan engines that constitute each regression relationship presented in Chapter Six. However, we deliberately excluded some engines. We excluded two engines, the TF34-100 and TF41-SPEY202, from the development cost sample because we were not certain that we had their complete development costs. We also excluded the TF30-103 engine from the development sample because the modification affected reliability and not performance. For the production data, we excluded the Harrier-type engines from the production-cost CER because those engines are statistically more costly to produce than the engines in the rest of the sample.

Table 5.3

Observations in Sample

Engine	Dash Number	Development Cost	Development Time	Production Cost
TF30P	-8	X	X	X
	-12/12A	X	X	N/I
	-7	X	X	N/I
	-408	X	X	N/I
	-412	X	X	X
	-100/111	X	X	X
	-414A	X	X	X
	-6	N/I	N/I	X
	-1	N/I	N/I	X
	-3	N/I	X	X
TF33P	-1/3	X	X	X
	-5/9	N/I	N/I	X
	-7/7A	N/I	N/I	X
TF34GE	-2	X	X	X
	-400	X		X
	-100	N/I	X	X
TF39A	-1	X	X	N/I
TF41A	-1	X	X	X
	-2	X	X	X
	-402	X	N/I	N/I
	SPEY202	N/I	X	N/I
F100PW	-100	X	X	X
	-220	X	X	X
	-229	X	X	X
F101GE	-100	X	X	N/I
F105PW	-100	N/I	X	N/I
F109GA	-100	X	X	N/I
F110GE	-100	X	X	X
	-400	X	N/I	X
	-129	X	X	X
F117PW	-100	N/I	X	N/I
F119PW	-100	X	X	N/I
F120GE	-100	X	X	N/I
F402RR	Pegasus 5	X	X	N/I
	Pegasus 6	X	X	N/I
	-401	X	X	N/I
	-406	X	N/I	N/I
	-408	X	N/I	N/I
	-402	N/I	N/I	N/I

Table 5.3—Continued

Engine	Dash Number	Development Cost	Development Time	Production Cost
F404GE	-400	X	X	X
	-400D	X	N/I	N/I
	-RM12	X	X	N/I
	-402	N/I	N/I	N/I
F414	-400	X	N/I	X
JT8D	-9	X	X	N/I
JT9D	-3	X	X	N/I
	-7	X	N/I	N/I
	-7Q	X	N/I	N/I
	-7R4D	X	N/I	N/I
	-59A	X	N/I	N/I
F405RR	-400	N/I	N/I	X

NOTES: Development and production cost data are not shown due to their proprietary nature; X = included; N/I = not included.

Data Verification Process

To verify the programmatic, performance, and cost data provided by NAVAIR, we compared that data with information from previous RAND studies and other sources.[5] To validate the data further, we also used Contractor Cost Data Reports (CCDRs) from some more-recent engine development efforts.[6] Comparison data for all the engines used in our analysis were not available; for those engines for which the data were available, performance parameters and technical characteristics were the same among all of our sources. However, the differences in the development cost data among some sources were pronounced. Figure 5.3 compares the differences between the reported development cost data from each source and the develop-

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[5] The other sources contain proprietary contractor information and are for U.S. government use only. They were by Cote and Lilly (1985) for the Naval Air Development Center (NADC), Daley and Richey (1994) for the Naval Center for Cost Analysis (NCCA), and the Ketron Division of the Bionetics Corporation (1998) for the Naval Air Systems Command. Any proprietary information contained in those analyses are not included in this report. General Electric, the manufacturer of some of the engines used in our analysis, and the Air Force Cost Analysis Agency also provided cost data on some engine developments.

[6] CCDRs contain contract cost information and are required by most DoD development contracts.

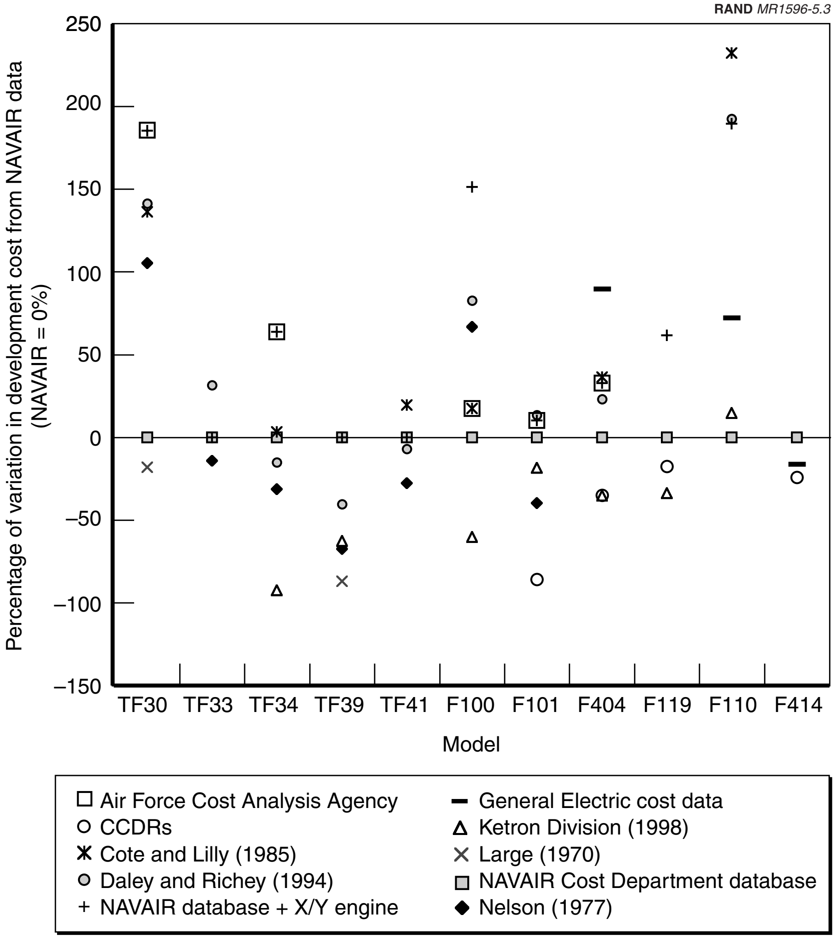

Figure 5.3—Differences Between Development Cost Data from Various Sources and NAVAIR Development Cost Data

ment cost data provided by NAVAIR. The variation in the differences is large, particularly the variation between data from older sources and from sources reporting on more-recent developments in engine technology.

Most of the differences between the NAVAIR data and the other sources are probably due to the grouping of related developments into a single observation. This grouping of developments into a single observation was a problem with some of the older studies. In some studies, it was clear which dash numbers were included in a group; in other studies, it was not. Another source of variation is whether the related experimental engine (the "X" or "Y" prototype engine) was included in the development cost (see the "Daley and Richey" and "NAVAIR database + X/Y engine" values in Figure 5.3). For our analysis, we isolated development costs by dash number and excluded the experimental engine cost. Of all the cost data we examined, the NAVAIR cost data were the most consistent with our approach. Other minor differences between NAVAIR data and other sources are likely due to various adjustments that were made to the cost data by researchers in earlier studies to state the values on a fixed-year basis.[7]

Normally, in parametric analysis, the dependent term (y) is known fairly accurately. However, with this example, significant uncertainty exists in how accurately we know the "true" development cost. Provided that the uncertainty is truly random (i.e., we have not introduced a systematic bias), the information can still be used for parametric purposes; however, one should expect the residual errors to be relatively high for any relationship. To perform a similar validation on our production data, our sources of alternative data were much more limited. The only studies to which we had access and that had published unit lot costs and technical and performance data were Nelson (1977) and Large (1970). The production values in RAND studies prior to this one and the NAVAIR data differed by only a few percentage points.

In this chapter, we summarized the parameters for the various turbofan engines in our database and our efforts at validating those data. We also described a series of technical risk and maturity measures that we applied to each engine. In the next chapter, we use that data and those measures to develop CERs for development cost, development time, and production cost of military jet engines.

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[7] An exact time frame is not shown in Figure 5.3 due to the sensitive nature of that data.

Chapter Six

STATISTICAL ANALYSIS

In this chapter, we describe the parametric development cost, production cost, and schedule estimating relationships that we found when analyzing historical turbofan engine cost data. We determined each of the cost-estimating relationships through a series of least-square regressions (both stepwise and ordinary) using the criteria for including parameters in developing parametric relationships described in Chapter Five.

In determining these relationships, we were unable to incorporate, or chose not to use, all the available parameters from the database. First, we have far too few observations (i.e., too few degrees of freedom) to create relationships that complex. Second, some parameters do not correlate significantly with respect to the dependent variable. For example, we did not see any meaningful difference between Navy and Air Force engines (after accounting for the other parameters). Third, many of the parameters themselves are correlated. For example, thrust-to-weight ratio could be used instead of rotor inlet temperature as a parameter in a development-cost parametric relationship. However, the resulting relationship would be slightly less desirable from a statistical standpoint. In any event, one should not include both of those variables in determining the resulting cost-estimating relationship because either parameter would serve to explain the same sort of variance in the sample—i.e., both are proxies for technological risk and improvement.[1]

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[1] A cost estimating relationship is basically a regression model where the dependent variables (in our case, development cost, development schedule and productions cost) are correlated to a series of independent variables. The goal of this analysis is to use

It is important to note that we are not showing cause and effect between any two given variables but, rather, statistically significant correlations between any two given variables. Table 6.1 presents all the parameters we explored in determining each parametric relationship for engine cost and development times and outlines the reason for retaining them or rejecting them from the analysis. Note that we may have explored one or more forms of a parameter (e.g., the log of a parameter). The table summarizes all the "best" regression analysis results for a particular parameter.

In the following section, we report the results of our regression analysis for development cost, development time, and production unit cost, along with relevant statistical information such as residual error (i.e., root mean square error [RMSE]), R-squared, and the t-statistic. (At the end of this chapter, we present our recommended parametric estimating relationships.)

DEVELOPMENT COST

Development cost includes all costs to design, develop, and test an engine. Engine programs and the corresponding parameters that were used in this analysis are identified in Tables 6.2 and 6.3.[2]

The parametric relationships for aircraft engine development cost are described next along with some summary statistical information. Based on our assessment, the development cost data are separated into two populations of engines:

1. **New Engines**. New engines are engines that employ advanced technology, are a new centerline development, or are the first engines in a series order.[3] If any of these criteria apply, the engine falls into this category, even if the engine is a follow-on engine in a series. The New Engine column in Table 6.3 identifies with a 1

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those variables that best explain the independent variable and avoid having two variables that are closely linked and represent the same effect, such as technological improvement or technological changes.

[2] Data on all the engines listed in Tables 6.2 and 6.3 do not necessarily include both development cost and schedule information. For some of the engines, we were able to obtain only development cost or schedule data.

[3] See Chapter Five for a detailed discussion of engine development categories.

Table 6.1

Parameters Evaluated in the Regression Analysis

	Development Cost			
Parameter	New	Simple Derivative	Development Time	Production Cost
Thrust	B	C	B	C
Specific fuel consumption	B	S	B	A
Air flow	B	B	B	A
Overall pressure ratio	C	C	S	C
Rotor inlet temperature	S	S	C	S
Dry weight	B	C	B	S
Thrust to weight	C	B	C	C
Afterburning (yes/no)	C	B	C	S
NAVAIR technical scale	C	B	C	C
Full-scale test hours	B	S	B	B
Low-rate production release date/MQT	C	C	C	C
Contract authorization date	C	C	C	B
Delta TOA	B	B	C	B
Series order	B	B	D	B
SOA (based on thrust-to weight ratio)	B	B	C	B
SOA (based on RIT)	C	B	B	B
Navy development	B	B	C	B
Air Force development	B	B	C	B

A = A sign (+/-) on the coefficient does not make logical sense using a single variable regression. B = Parameter is not statistically significant nor is it driven by a leveraging observation (e.g., technology parameters explained by one of the performance variables). C = Parameter is correlated with a more significant parameter. D = Distribution of residuals with respect to the parameter is not normal. S = Significant and included in regression.

Table 6.2

Development Cost and Time Relationship: Performance and Schedule Input Values

Engine	Thrust (at Intermediate Rating Point) (kg/second)	Specific Fuel Consumption	Overall Pressure Ratio	Rotor Inlet Temperature (F°)	Thrust-to-Weight Ratio	Air Flow (lbs/second)	Dry Weight (lbs)	Afterburner (Yes=1/No=0)	Full-Scale Test Hours	Low Rate Production Release	Contract Award
TF30P-3	10,750	0.63	17.1	2,174	4.77	233	3,880	1	15,908	Jul 1965	Sept 1959
TF30P-8	12,200	0.68	18.8	2,035	4.83	256	2,526	0	13,217	Mar 1967	Nov 1965
TF30P-12/12A	12,290	0.69	17.5	2,100	5.03	247	4,027	1	7,808	Apr 1968	Nov 1965
TF30P-7	12,350	0.69	17.5	2,070	4.94	242	4,121	1	7,967	Mar 1969	Apr 1968
TF30P-408	13,400	0.64	18.8	2,090	5.15	256	2,602	0	9,717	May 1970	Mar 1969
TF30P-412	12,350	0.69	19.8	2,150	5.27	242	3,969	1	6,233	Mar 1971	Oct 1969
TF30P-100/111	14,560	0.69	21.8	2,055	6.24	260	4,022	1	1,933	Jul 1971	Jan 1970
TF30P-414A	12,350	0.69	19.8	2,150	5.27	242	3,969	1	32,817	Sept 1981	Oct 1978
TF33P-1/3	17,000	0.52	13.0	1,600	4.36	450	3,900	0	2,500	Apr 1960	Jan 1958
TF34GE-2	8,165	0.35	21.9	2,054	5.75	318	1,421	0	11,200	Aug 1972	Mar 1968
TF34GE-100	7,990	0.36	19.8	2,234	5.60	314	1,427	0	4,100	Aug 1974	Jun 1972
TF34GE-400	8,159	0.35	21.9	2,142	5.52	338.3	1,478	0	10,367	Mar 1985	N/A
TF39A-1	37,751	0.32	22.0	2,380	4.78	1444	7,900	0	8,660	Jul 1969	Sept 1966
SPEY 202	12,250	0.64	16.9	2,043	4.94	234	4,093	1	48,500	Nov 1967	Jun 1965

Table 6.2—Continued

Engine	Thrust (at Intermediate Rating Point) (kg/second)	Specific Fuel Consumption	Overall Pressure Ratio	Rotor Inlet Temperature (F°)	Thrust-to-Weight Ratio	Air Flow (lbs/second)	Dry Weight (lbs)	After-burner (Yes=1/ No=0)	Full-Scale Test Hours	Low-Rate Production Release	Contract Award
TF41A-1	14,500	0.65	21.0	2,157	4.57	260	3,175	0	3,050	Dec 1968	Sept 1966
TF41A-2	15,000	0.66	21.4	2,157	4.62	263	3,246	0	3,700	Jul 1969	Sept 1968
TF41A-402	15,000	0.66	21.4	2,157	4.55	263	3,296	0	24,561	Jun 1987	N/A
F100PW-100	14,690	0.72	27.7	2,565	7.8	228	3,056	1	13,305	Oct 1973	Mar 1970
F100PW-220	14,590	0.73	25.0	2,600	7.16	224	3,179	1	37,989	Jun 1985	Jun 1981
F100PW-229	16,999	0.70	26.9	2,730	8.53	248	3,400	1	3,000	Sept 1988	Jun 1985
F101GE-100	17,200	0.58	26.5	2,550	7.02	352	4,382	1	11,200	Jun 1976	Jun 1970
F109GA-100	1,330	0.39	20.7	1,976	3.33	52.3	400	0	10,180	Sept 1985	Jul 1982
F110GE-100	14,020	0.67	29.9	2,405	7.01	260	3,830	1	5,522	Jan 1985	Jan 1981
F110GE-400	16,333	0.69	29.9	2,528	6.11	261.2	4,412	1	4,749	N/A	May 1984
F110GE-129	17,084	0.68	31.2	2,484	7.41	267	3,980	1	2,100	Sept 1988	Jun 1985
F117PW-100	40,000	0.35	29.5	2,400	5.58	1226	7,164	0	2,900	Feb 1987	Apr 1984
F119PW-100	20,500	0.80	26.0	3,000	7.95	270	3,900	1	13,325	Jan 1993	Nov 1988

Table 6.2—Continued

Engine	Thrust (at Intermediate Rating Point) (kg/second)	Specific Fuel Consumption	Overall Pressure Ratio	Rotor Inlet Temperature (F°)	Thrust-to-Weight Ratio	Air Flow (lbs/second)	Dry Weight (lbs)	Afterburner (Yes=1/No=0)	Full-Scale Test Hours	Low-Rate Production Release	Contract Award
F120GE-100	20,300	0.80	24.0	3,000	8.13	275	4,000	1	13,905	Jan 1993	Nov 1988
Pegasus 5	15,500	0.63	13.7	1,990	4.59	394	3,380	0	4,000	Oct 1964	Oct 1962
Pegasus 6	19,000	0.64	13.8	2,160	5.29	409	3,591	0	6,500	Oct 1968	Oct 1966
F402RR-401	20,500	0.65	14.7	2,215	5.51	409	3,720	0	5700	Jun 1971	May 1969
F402RR-406	21,500	0.66	14.7	2,260	5.70	437	3,770	0	8,300	N/A	N/A
F402RR-408	23,390	0.75	15.5	2,467	6.00	459	3,900	0	2,301	N/A	Sep 1987
F404GE-400	10,600	0.81	24.0	2,459	7.48	140	2,140	1	14,900	Jun 1979	Nov 1975
F404GE-400D	10,800	0.82	25.0	2,534	6.02	142	1,795	0	11,400	N/A	Mar 1985
F404GE-RM12	11,500	0.70	26.0	2,535	7.79	150	2,310	1	5,250	Dec 1987	Jun 1981
F414GE-400	14,327	0.84	27.2	2,757	8.68	174	2,445	1	10,463	Nov 1996	N/A
JT8D-9	14,500	0.60	15.9	1,720	4.46	318	3,252	0	6,067	Jan 1963	Mar 1960
JT9D-3	43,600	0.37	21.5	2,300	4.93	1,510	8,850	0	4,800	Jan 1970	Jun 1966
JT9D-7	45,600	0.36	22.3	2,350	5.15	1,535	8,850	0	13,100	Jun 1971	N/A
F105PW-100	45,600	0.36	22.3	2,405	5.15	1,535	8,850	0	N/A	Jun 1971	Aug 1967
JT9D-59A	53,000	0.37	24.5	2,400	5.99	1,640	8,850	0	23,600	Dec 1974	N/A
JT9D-7Q	53,000	0.37	24.5	2,400	5.70	1,640	9,295	0	22,500	Oct 1978	N/A
JT9D-7R4D	48,000	0.34	23.0	2,320	5.39	1,575	8,905	0	14,300	Nov 1980	N/A

NOTES: Air flow = The rate of airflow through an engine, measured in pounds of air per second; AF = U.S. Air Force; N = U.S. Navy; USMC = U.S. Marine Corps; C = Commercial; N/A = Not available.

Table 6.3

Development Cost and Time Relationship: Technical Risk and Maturity Input Values

Engine	Delta TOA	NAVAIR Technical Scale	New Centerline Design (Yes=1/ No=0)	Advanced Technology (Yes=1/ No=0)	Series Order	New Engine (Yes=1/ No=0)	Simple Derivative (Yes=1/ No=0)	SOA (RIT)	SOA (Thrust-to-Weight)	Service
TF30P-3	8722.85	2.1	1	1	2	0	0	0.97605	1.08573	AF
TF30P-8	9322.66	4	1	0	4	1	0	0.94108	0.83295	N
TF30P-12/12A	8723.32	5	0	0	4	0	1	0.93983	0.86744	AF
TF30P-7	8105.74	1.1	0	0	5	0	1	0.90067	0.77415	AF
TF30P-408	8596.46	2.1	0	0	6	0	1	0.88756	0.78410	N
TF30P-412	8099.61	4	0	0	7	0	1	0.89164	0.80237	N
TF30P-100/111	7168.73	5	0	0	8	0	1	0.85225	0.92376	AF
TF30P-414A	4262.61	5	0	0	9	0	1	0.80238	0.66678	N
TF33P-1/3	7789.01	2	0	0	1	1	0	0.99400	1.05156	AF
TF34GE-2	8496.83	3.2	0	0	1	1	0	0.83473	0.90109	N
TF34GE-100	9492.86	2	0	0	2	0	0	0.87876	0.79266	AF
TF34GE-400	4666.49	3	0	0	3	0	1	0.78438	N/A	N

Table 6.3—Continued

Engine	Delta TOA	NAVAIR Technical Scale	New Centerline Design (Yes=1/ No=0)	Advanced Technology (Yes=1/ No=0)	Series Order	New Engine (Yes=1/ No=0)	Simple Derivative (Yes=1/ No=0)	SOA (RIT)	SOA (Thrust-to-Weight)	Service
TF39A-1	9416.21	7	1	1	1	1	0	1.03556	0.79569	AF
SPEY 202	8381.66	8	0	0	1	0	0	0.94478	0.85192	N/A
TF41A-1	9356.87	2.1	0	0	2	0	1	0.96534	0.76073	AF
TF41A-2	9106.86	1.1	0	0	3	0	1	0.93853	0.72400	N
TF41A-402	2536.64	1	0	0	4	0	1	0.78252	N/A	N
F100PW-100	11366.5	8	1	1	1	1	0	1.02370	1.15470	AF
F100-PW-220	7347.95	1	0	0	2	0	1	0.95209	0.86498	AF
F100PW-229	7242.89	2	0	1	3	1	0	0.98581	0.97194	AF
F101GE-100	9470.89	8	1	1	2	1	0	0.97499	1.03923	AF
F109GA-100	5323.62	8	1	0	1	1	0	0.72359	0.39632	AF
F110GE-100	5313.41	6	0	0	2	0	1	0.88069	0.84686	AF
F110GE-400	N/A	1	0	0	3	0	1	N/A	0.70623	N
F110GE-129	4603.42	2	0	0	4	0	1	0.89698	0.84432	AF
F117PW-100	3328.22	2	0	0	2	0	0	0.87068	0.64497	AF
F119PW-100	N/A	8	1	1	2	1	0	N/A	N/A	AF
F120GE-100	N/A	8	1	1	2	1	0	N/A	N/A	AF
Pegasus 5	9364.65	8	0	0	1	1	0	1.02579	0.89632	N/A
Pegasus 6	9233.23	4	0	1	2	1	0	0.96668	0.88059	N/A
F402RR-401	8669.8	3	0	0	3	0	1	0.91860	0.83891	N
F402RR-406	N/A	5	0	0	4	0	1	N/A	N/A	USMC
F402RR-408	N/A	5	0	0	5	0	1	N/A	N/A	USMC
F404GE-400	9071.73	7	1	0	2	1	0	0.92657	0.99341	N

Table 6.3—Continued

Engine	Delta TOA	NAVAIR Technical Scale	New Centerline Design (Yes=1/ No=0)	Advanced Technology (Yes=1/ No=0)	Series Order	New Engine (Yes=1/ No=0)	Simple Derivative (Yes=1/ No=0)	SOA (RIT)	SOA (Thrust-to-Weight)	Service
F404GE-400D	N/A	1	0	0	4	0	1	N/A	0.68594	N
F404GE-RM12	6536.52	6	0	0	3	0	1	0.91966	0.94109	N/A
F414GE-400	5347.38	8	0	1	1	1	0	0.99556	N/A	N
JT8D-9	7895.13	2	0	0	1	1	0	0.92603	N/A	AF
JT9D-3	8407.6	7	1	1	1	1	0	0.97674	N/A	C
JT9D-7	8281.93	3	0	0	2	0	1	0.97459	N/A	C
F105PW-100	8715.91	1.1	0	0	3	0	0	0.99740	0.83141	AF
JT9D-59A	7397.27	5	0	0	4	0	1	0.94406	N/A	C
JT9D-7Q	5911.53	2.1	0	0	5	0	1	0.90872	N/A	C
JT9D-7R4D	4595.92	2	0	0	6	0	1	0.86999	N/A	C

NOTES: Air flow = The rate of airflow through an engine, measured in pounds of air per second; AF = U.S. Air Force; N = U.S. Navy; USMC = U.S. Marine Corps; C = Commercial; N/A = Not available; Delta time of arrival = time when the engine technology is available.

those engines that meet these criteria and for which development cost information was available. As we noted in Chapter Five, cost information was not available for all the engines listed in Tables 6.2 and 6.3.

2. **Simple Derivatives**. Any engines that do not fall into the first category are in this population. These engines are identified in Table 6.3 by a 1 in the Simple Derivative column, provided the cost data were available.

Disappointingly, the residual error (the RMSE) remains rather high for the parametric relationships for both the development cost and development schedule, particularly for derivative engines. This high error should not be completely unexpected given that our uncertainty regarding the dependent variable is fairly high (see the discussion on data verification in Chapter Five). The estimating relationships for development cost and schedule are useful only at the conceptual stage of engine development and require caution given the range of uncertainty of the estimate. One should not draw conclusions based on small differences in predicted values. Furthermore, the relationships should not be used for estimate validation.

Table 6.4 shows the regression results and data summary for new engines.[4] Figure 6.1 shows the corresponding residual plot for new engines. The residual error is the difference between the actual value and the predicted value. The smaller the residual, the better the model "fit" to that observation. In essence, the points should be normally distributed around zero with no pattern.[5] Similar information is shown in Table 6.5 and Figure 6.2 for the simple derivative engines.

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[4] RMSE is essentially the sample standard deviation of the forecasted errors without any degrees-of-freedom adjustment. R-squared, the coefficient of determination, describes the percent of variance explained by the estimate equation. Adjusted R-squared takes into account the degrees of freedom that were lost in the analysis. A value of R-squared closer to one suggests that the estimated regression equation fits the sample data very well, whereas a value closer to zero shows a failure of the estimated regression equation to forecast the sample data. The t-statistic (based on the Student t-test) provides information on the level of significance of the calculated coefficient. It is reported in parentheses below each parameter in Table 6.4 and later tables in this chapter.

[5] The residual plot is useful for diagnosing model misspecification and heteroskedacticity and for potentially identifying outlying observations.

Table 6.4

Development Cost Results for New Engines

Variable	Number of Obser-vations	Mean	Median	Standard Deviation	Minimum	Maximum
lnrd01m	16	6.730	6.835	0.831	5.321	7.910
lnritf	16	7.737	7.758	0.187	7.378	8.006

lnrd01m = –24.429 + 4.027 lnritf
(7.97)

R-squared = 0.8194.

Adjusted R-squared = 0.8066.

RMSE = 0.36546.

lnrd01m = natural log of the development cost in 2001 $millions.

lnritf = natural log of the rotor inlet temperature in degrees Fahrenheit.

NOTE: In this table, and in similar tables that follow in this chapter, the t-statistic for a parameter is shown in parentheses below the parameter.

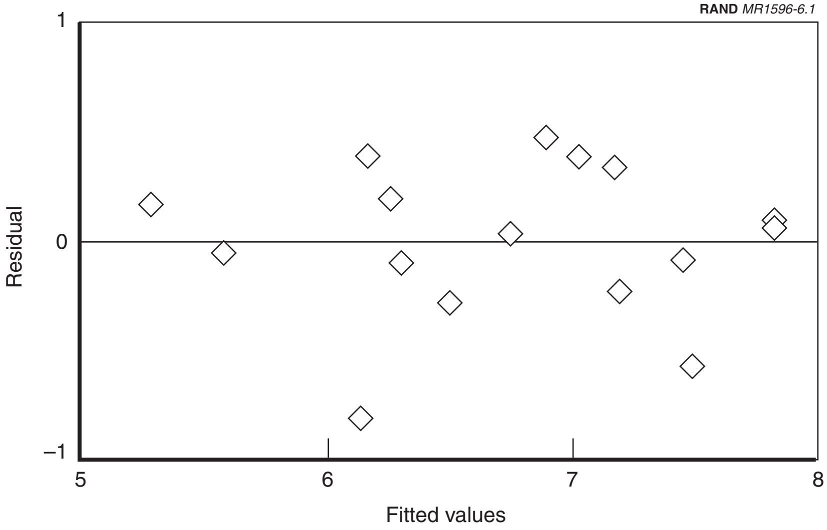

Figure 6.1—Residual Plot Graph for New Engine Development Cost

Table 6.5

Development Cost Results for Simple Derivative Engines

Variable	Number of Obser-vations	Mean	Median	Standard Deviation	Minimum	Maximum
lnrd01m	23	5.667	5.432	0.923	3.931	7.544
lnritf	23	7.735	7.723	0.076	7.628	7.863
lnsfc	23	–0.516	–0.400	0.281	–1.079	–0.198
lnfsth	23	9.007	8.983	0.863	7.567	10.545

$$\mathbf{lnrd01m = -39.422 + \underset{(4.45)}{5.066\,lnritf} - \underset{(-3.90)}{1.299\,lnsfc} + \underset{(5.33)}{0.582\,lnfsth}}$$

R-squared = 0.8332.

Adjusted R-squared = 0.8068.

Root mean square error (MSE) = 0.40575.

lnrd01m = natural log of the development cost in 2001 $millions.

lnritf = natural log of the rotor inlet temperature in degrees F.

lnsfc = natural log of the specific fuel consumption (lb/hour/lb).

lnfsth = natural log of full-scale test hours.

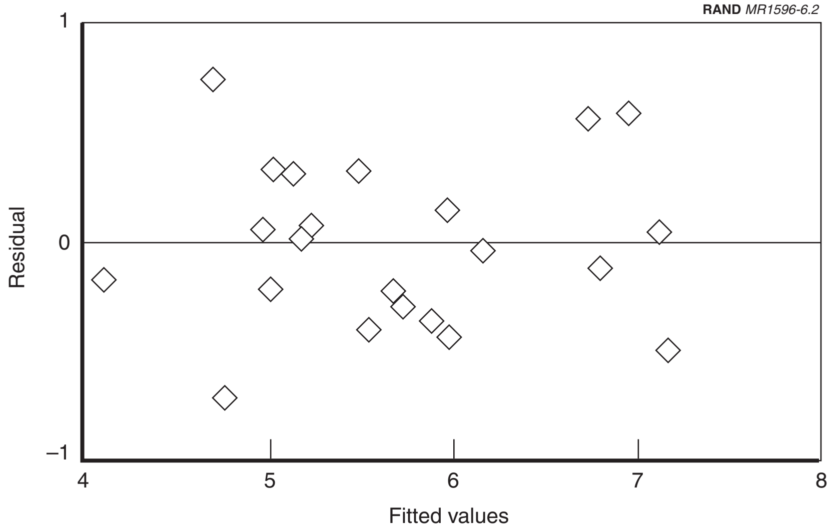

Figure 6.2—Residual Plot Graph for Simple Derivative Engine Development Cost

It is interesting to note that for the new engine developments, basic performance measures define the CER. There was no significant technical maturity/risk measure that correlated with development cost and development schedule. For the simple derivative engines, by comparison, a term dependent on the number of full-scale test hours appears to be correlated. While this term was categorized as "programmatic," it is also partially related to technical risk and maturity. One would expect that a more complex, technically challenging derivative engine would require more test hours than a simpler one.

DEVELOPMENT TIME

The parametric relationship for aircraft engine development time is shown in Table 6.6 with summary information on statistics. Figure 6.3 shows the corresponding residual plot for new engines. The data included in Tables 6.2 and 6.3 for the development time analysis are for only those engines listed in Table 5.3 in Chapter Five. While the t-statistics indicate that both parameters (2.876 and 3.581) are significant, the regression statistics (R-squared and RMSE) are very poor.

Table 6.6

Development Time Regression Results

Variable	Number of Observations	Mean	Median	Standard Deviation	Minimum	Maximum
lndtimem	33	3.473	3.527	0.510	2.298	4.357
neweng	33	0.515	1.000	0.508	0.000	1.000
lnopr	33	3.038	3.063	0.233	2.565	3.440

$$\mathbf{lndtimem = -0.243 + 0.425\ neweng + 1.15\ lnopr}$$
$$\mathbf{(2.88)\qquad\qquad (3.58)}$$

R-squared = 0.3741.

Adjusted R-squared = 0.3324.

RMSE = 0.4169.

lndtimem = natural log of the development time in months (from contract award to low-rate production release; for older engines, the finish date corresponds to the MQT date).

neweng = a binary variable (1 or 0). It is true (1) when the engine is the first production engine of a family, incorporates advanced technology, or is a new centerline design. Otherwise, the variable is false (0).

lnopr = natural log of the overall pressure ratio.

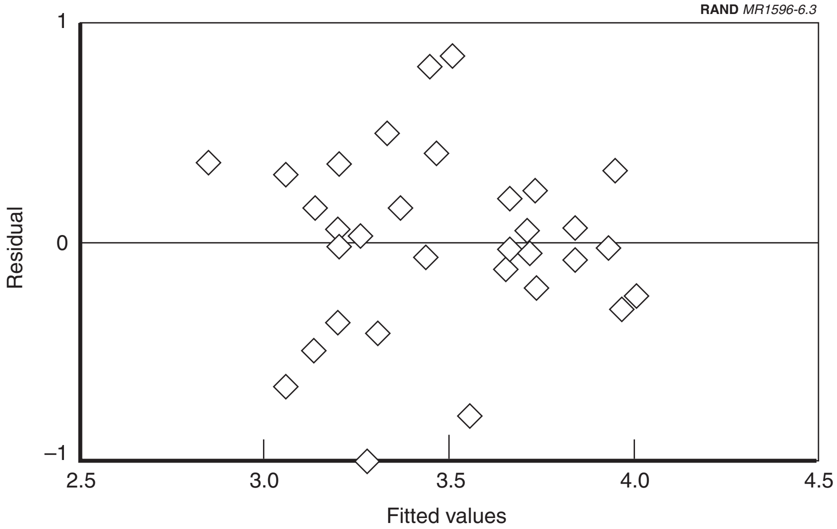

Figure 6.3—Residual Plot Graph for New Engine Development Times

PRODUCTION COST

Production cost includes all costs associated with the manufacture and delivery of an engine to the U.S. government (i.e., the customer).[6] The data used in the production cost estimating analysis are shown Table 6.7.

Normalizing the Data

For each engine in the production cost sample, we had data on lot quantity and unit price over several years. We first adjusted each unit price to a constant-year basis. Next, we fit the production for each engine to a unit-cost improvement curve to determine a T_1 (the first unit produced) value and the cost improvement slope value. We used the midpoint of each lot quantity as the unit number for each lot's

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[6] These costs exclude the costs of a starter, auxiliary power unit, and batteries.

unit price. The only exception was the first lot; for that lot we used a unit number that was one-third of its production number.

The degree to which each of the production histories fits a unit-cost improvement curve was mixed. Some engine production histories fit well, showing the classical exponential decrease in cost. Other histories initially showed a cost improvement and then leveled out. Some histories showed a negative improvement, i.e., unit cost increased over the production run. Figure 6.4 shows a histogram of the cost improvement slope values, and Table 6.8 shows the summary statistics of the cost improvement slope.

Table 6.7

Production CER Input Values

Engine	Rotor Inlet Temperature (degrees F)	Dry Weight (lbs)	After Burner (Yes=1; No=0)
TF30P-6	2,050	2,716	0
TF30P-1	1,970	3,880	1
TF30P-3	2,174	3,880	1
TF30P-8	2,035	2,526	0
TF30P-412	2,150	3,969	1
TF30P-100/111	2,055	4,022	1
TF30P-414A	2,150	3,969	1
TF33P-1/3	1,600	3,900	0
TF33P-5/9	1,600	4,275	0
TF33P-7/7A	1,750	4,612	0
TF34GE-2	2,054	1,421	0
TF34GE-100	2,234	1,427	0
TF34GE-400	2,142	1,478	0
TF41A-1	2,157	3,175	0
TF41A-2	2,157	3,246	0
F100PW-100	2,565	3,056	1
F100PW-220	2,600	3,179	1
F100PW-229	2,730	3,400	1
F110GE-100	2,405	3,830	1
F110GE-400	2,528	4,412	1
F110GE-129	2,484	3,980	1
F404GE-400	2,459	2,140	1
F414GE-400	2,757	2,445	1
F405RR-400	2,100	1,524	0

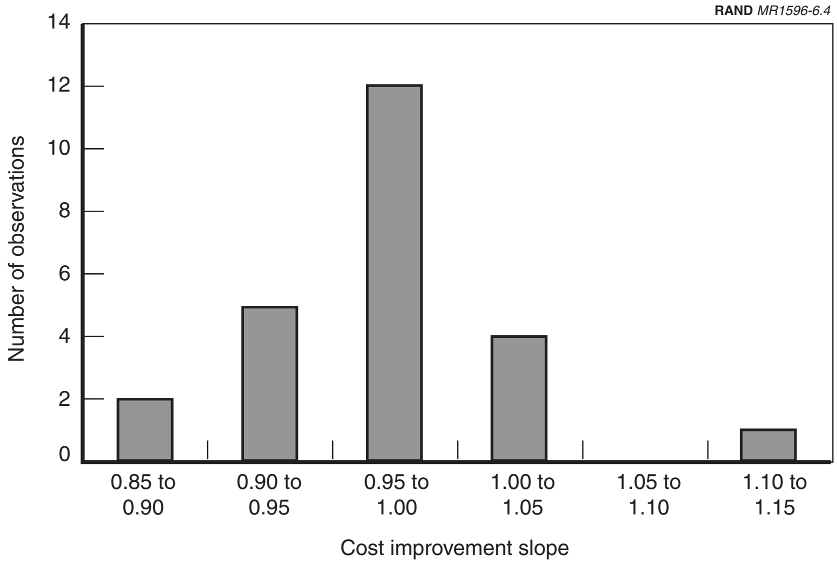

Figure 6.4—Histogram of Cost Improvement Slopes

Table 6.8

Cost Improvement Slope Summary

Variable	Number of Obser- vations	Mean	Median	Standard Deviation	Minimum	Maximum
lnslope	24	0.970	0.970	0.050	0.893	1.102

The cost improvement slope exhibits some correlation with thrust-to-weight ratio (shown in Table 6.9), as shown in Equation (1):

$$\text{lnslope} = 0.168 - \underset{(-3.26)}{0.116}\ \text{lntwt} \qquad (1)$$

where, R-squared = 0.3255, adjusted R-squared = 0.2948, root MSE = 0.04311, and lntwt is the natural log of the thrust-to-weight ratio (for maximum thrust and dry weight) and lnslope is the natural log of the cost improvement slope (in decimal form).

Production Cost CER

Our dependent variable for production cost will be the cost given some specific unit number. However, the question is, what is the appropriate unit number? Previous studies have developed relationships at unit 1000 (T_{1000}) (Large, 1970; Anderson, 1972; Nelson and Timson, 1974; Nelson, 1977; Nelson et al., 1979; Birkler, Garfinkle, and Marks, 1982) while others have used unit 100 (T_{100}) (for example, Daley and Richey, 1994). To determine the appropriate unit number, we initially developed a regression equation for a T_1 (unit 1) relationship that included a term that was related to the log of the cost improvement slope. The regression results are shown in Table 6.9, and Figure 6.5 shows the corresponding residual plot for new engines.

Table 6.9

Production Cost Regression

Variable	Observations	Mean	Median	Standard Deviation	Minimum	Maximum
$\ln T_1$	24	1.157	1.258	0.723	–0.099	2.273
lnslope	24	–0.032	–0.031	0.051	–0.114	0.097
lnritf	24	7.688	7.675	0.147	7.378	7.922
ab	24	0.542	1.000	0.509	0.000	1.000
lndrywt	24	8.005	8.108	0.381	7.259	8.436

$$\ln T_1 = -10.40 - \underset{(-13.02)}{8.550}\ \text{lnslope} + \underset{(4.59)}{0.482}\ \text{ab} + \underset{(3.63)}{1.162}\ \text{lnritf} + \underset{(2.42)}{0.262}\ \text{lndrywt}$$

R-squared = 0.9703.

Adjusted R-squared = 0.9641.

RMSE = 0.13703.

$\ln T_1$ = natural log of the production price for unit Number 1 in 2001 $millions.

lnslope = natural log of the cost improvement curve slope.

ab = binary variable (1) if it is an afterburning engine, (0) if not.

lndrywt = natural log of the dry weight for the engine in pounds.

lnritf = natural log of the rotor inlet temperature in degrees Fahrenheit.

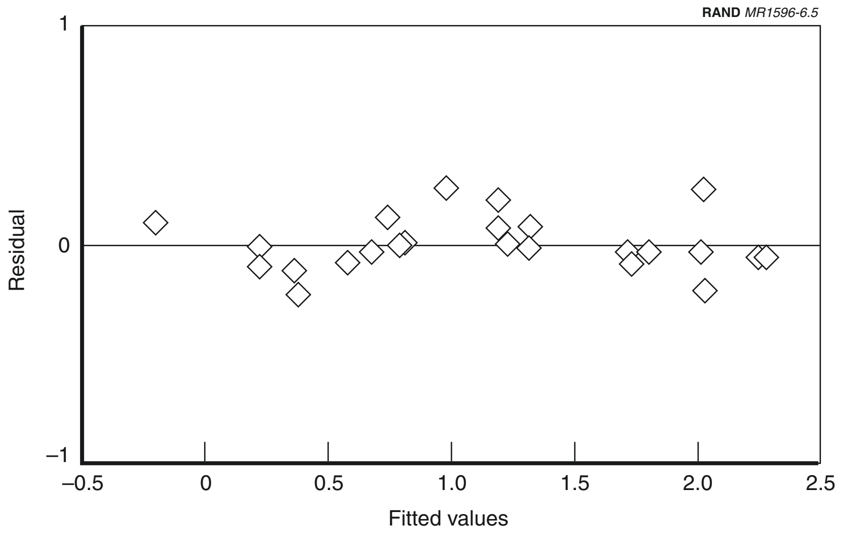

Figure 6.5—Production Cost Residual Plot Graph

Based on the coefficient for the lnslope term (see Table 6.9), one can determine a unit number, where the slope term and unit number term cancel one another. In other words, our general CER formulation is:

lnT1 = c * lnslope + (other terms) (2)

where c is the coefficient for the lnslope term in the regression. We also know that the unit cost improvement curve has the form

lnTx = lnT1 + lnslope / ln(2) * ln(x). (3)

Substituting Equation (2) for lnT1 in Equation (3), one arrives at

lnTx = c * lnslope + lnslope / ln(2) * ln(x) + (other terms). (4)

One can thus choose a unit number x such that the first two terms in Equation (4) cancel each other out. This cancellation occurs when

$$-c * = \ln(x) \,/\, \ln(2) \tag{4}$$

or

$$x = e\hat{}[-c * \ln(2)]. \tag{5}$$

Based on the production cost regression in Table 6.9, the unit number for x is about 375. It is interesting to speculate why the regression would converge to this unit number. Some of the military engine contractors/producers we interviewed for this study said that cost improvement slopes increase (or flatten) around unit numbers of 250 to 300. However, our production data do not show a consistent leveling off at that point. The similarity of the two values (250 and 300) might be a coincidence. Nonetheless, the unit value falls between those two values in previous RAND military engine studies. The regression analysis in Table 6.9 was redetermined to illustrate the cost estimate at a different point in the production using computed T_{375} values. The results of redetermining the regression are shown in Equation (6):

$$\mathrm{lnT375} = -10.4 + \underset{(3.745)}{1.162\ \mathrm{lnritf}} + \underset{(4.894)}{0.482\ \mathrm{ab}} + \underset{(2.55)}{0.262\ \mathrm{lndrywt}} \tag{6}$$

where R-squared = 0.9158, adjusted R-squared = 0.9032, RMSE = 0.13356, and where lnT375 is the natural log of the production price for unit number 375 in millions of 2001 dollars.

APPLYING THE RESULTS: A NOTIONAL EXAMPLE

We now discuss how the results of this study, summarized in Table 6.10, can be applied to a notional future engine.

To illustrate the use of the cost and time estimating relationships presented in this chapter, we now consider two preliminary aircraft designs, each of which employ a single afterburning engine for a single-engine fighter/attack aircraft. The first engine is an advanced derivative of an existing engine; the other engine is also derivative, but it employs more evolutionary technological advances. Table 6.11 describes the parameters of each engine.

Table 6.10

Summary of Parametric Relationships

Development Cost—New Engine	$\text{lnrd01m} = -24.429 + \underset{(7.97)}{4.027\ \text{lnritf}}$
Development Cost—Derivative	$\text{lnrd01m} = -39.422 + \underset{(4.45)}{5.066\ \text{lnritf}} - \underset{(-3.89)}{1.299\ \text{lnsfc}} + \underset{(5.32)}{0.582\ \text{lnfsth}}$
Development Time	$\text{lndtimem} = -0.243 + \underset{(2.88)}{0.425\ \text{neweng}} + \underset{(3.58)}{1.151\ \text{lnopr}}$
Production Cost—T_1	$\text{lnT1} = -10.40 - \underset{(-13.02)}{8.550\ \text{lnslope}} + \underset{(4.60)}{0.482\ \text{ab}} + \underset{(3.63)}{1.162\ \text{lnritf}} + \underset{(2.42)}{0.261\ \text{lndrywt}}$
Production Cost—T_{375}	$\text{lnT375} = -10.40 + \underset{(3.74)}{1.162\ \text{lnritf}} + \underset{(4.89)}{0.482\ \text{ab}} + \underset{(2.55)}{0.262\ \text{lndrywt}}$

lnrd01m = natural log of the development cost in 2001 $millions.

lnritf = natural log of the rotor inlet temperature in degrees Fahrenheit.

lnsfc = natural log of the specific fuel consumption (lb/hour/lb).

lnfsth = natural log of full-scale test hours.

lndtimem = natural log of the development time in months (from contract award to low-rate production release; for older engines, the finish date corresponds to the MQT date).

neweng = a binary variable (1 or 0). It is true (1) when the engine is the first production engine of a family, incorporates advanced technology, or is a new centerline design. Otherwise, the variable is false (0).

lnopr = natural log of the overall pressure ratio.

lnT1 = natural log of the production price for unit number 1 in 2001 $millions.

lnslope = natural log of the cost improvement curve slope.

ab = binary variable. It is (1) if the engine is an afterburning engine and (0) if it is not.

lndrywt = natural log of the dry weight for the engine in pounds; lnT375 = natural log of the production price for unit number 375 in 2001 $millions.

Using the CERs in Table 6.10, which summarized all the parametric relations presented in this chapter, in conjunction with the information provided in Table 6.11 yields the results shown in Table 6.12 for the two notional engine examples.

Table 6.12 shows that the development cost, development time, and the unit cost of the new engine design are significantly higher than the development cost, development time, and the unit cost of a derivative engine using evolutionary technologies. However, these costs must be weighed against performance gains, such as increased range, speed, maneuverability, and fuel efficiency, decreased overall

Table 6.11

Description of Two Notional Engines

	New Engine with Advanced Technologies or New Centerline	Derivative Engine with Evolutionary Technology Advances
Description of technology advances	Ceramic matrix composites in the hot section, including possibly the first stage of the turbine rotor Fluidic nozzle Variable cycle Integral starter Generator Advanced health-monitoring system	Advanced air cooling in the high-pressure turbine Variable cycle Integral starter Generator Advanced health-monitoring system Advanced air cooling in the high-pressure turbine
Rotor Inlet Temperature (F°)	3,545	3,300
Full-scale test hours	6,000	3,500
Overall pressure ratio	26	26
Specific fuel consumption ratio	0.8	0.8
Afterburning engine (yes = 1; no = 0)	1	1
Dry weight (pounds)	4,130	4,970
New engine design (yes = 1; no = 0)	1	0
Cost improvement slope	90%	95%

Table 6.12

Results of the Estimating Relationships for the Two Notional Engines

	New Engine (2001 Dollars)	Derivative Engine (2001 Dollars)
Development costs	$4,840 million	$780 million
Development time	51 months	33 months
Production cost for engine (T_1)	$14.3 million	$8.67 million
Production cost for engine (T_{375})	$5.8 million	$5.6 million

aircraft weight, greater potential for future performance growth, increased engine life, greater reliability and maintainability, and other gains.

SUMMARY

In this chapter, we presented cost-estimating relationships for aircraft turbofan engine development cost, development time, and production cost. In all cases, simple performance parameters and technical risk measures, such as full-scale test hours and new-engine-versus-derivative-engine parameters, were the most significant factors. Residual errors for development time and engine costs are high, precluding them from being used anywhere other than at the conceptual stage of aircraft development.

Chapter Seven

CONCLUSIONS

In this report, we presented a parametric estimating method for forecasting military turbofan engine development costs, development schedules, and production costs. We first discussed the technical parameters that drive both engine development cost and production cost. We then presented a quantitative analysis of actual historical data on engine costs.

Our principal focus was on adding new observations to the cost-estimating database from earlier RAND studies (Large [1970]; Nelson [1977]; Birkler, Garfinkle, and Marks [1982]) and updating the parametric relationships for aircraft turbofan engine cost and development times. We used a more recent set of cost data provided by NAVAIR to capture the effect of technological evolution that has occurred over the past two decades. We also extended and improved upon the prior RAND studies in a couple of ways. Most of the previous engine cost studies group turbojet and turbofan engine types into the same population. In this study, we focused exclusively on parametric relationships for turbofan engines. As such, we segregated the turbofan engine cost data from turbojet and turboshaft cost data. This approach provides a more homogenous population for the parametric cost analysis. In addition, we treated each engine model (or “dash number”) as a separate observation, whereas the earlier studies did not explicitly address how to treat a family of engine types.

In our statistical analysis, we explored most of the possible performance, programmatic, and technological parameters that affect engine development costs, production costs, and development schedules. Our results indicate that rotor inlet temperature is a significant variable in most of the reported estimating relationships. With the exception of new-engine versus derivative-engine parameters and full-scale test hours parameters, there were no other significant technical maturity/risk measures that correlated with the costs or development schedule for military jet engines.

Disappointingly, the residual error for the development cost and development time estimating relationships is rather high, particularly for the derivative engines. These relationships are useful only at the conceptual stage of engine technology development and require caution in how they are used in view of their range of uncertainty.

The results of our analysis also indicate that an advanced-technology new engine design would have significantly higher development costs and would take longer to develop than a derivative engine using evolutionary technologies.

Finally, given the high degree of uncertainty surrounding the direction of future military aircraft engine development, cost analysts should continue working with the engine manufacturing industry to monitor changes in practice and technology that will be incorporated into the aircraft that are the subject of their cost-estimating studies. Those analysts should also continue collecting data on the actual cost of aircraft jet engine development and production. Both practices will improve the quality of future cost-estimating tools.

Appendix A

AN EXAMINATION OF THE TIME OF ARRIVAL METRIC

In several previous RAND reports[1] on aircraft engine production and development costs, the authors employed a measure of technical maturity called the *delta time of arrival* (delta TOA). This metric is the difference between the predicted TOA and actual TOA (see Chapter Five). The predicted TOA is the forecast date that a particular engine model should enter low-rate production (or it is the MQT) based on the engine's technical characteristics. More technically advanced engines have a later TOA than less advanced ones. Therefore, a positive delta TOA would mean that an engine was produced sooner than was forecast; thus, the engine has a higher degree of technical risk. In this appendix, we discuss in detail an updated TOA metric and the use of delta TOA as a measure of aircraft engine technical advancement.[2]

UPDATING THE TOA METRIC

Based on our expanded sample of aircraft engines (compared with prior RAND studies), we reestimated the CER for TOA. The updated regression output (using the original formulation but including additional data), which includes both turbojet and turbofan engines, is shown in Table A.1.

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[1] See Large (1970); Anderson and Nelson (1972); Nelson and Timson (1974); Nelson (1977); and Birkler, Garfinkle, and Marks (1982).

[2] The discussion in this appendix assumes some knowledge of statistics on the part of the reader. For those without a statistics background, we can recommend the following basic texts: Berenson and Levine (1996) and *Stata Reference Manual* (1999).

Table A.1

Original TOA Formulation with New Data

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	174423.58	5	34884.72
Residual	50215.84	99	507.23
Total	224639.43	104	2159.99

newTOA	Coefficient	Standard Error	t-statistic	P>|t|[a]	95% Confidence Interval	
lnritf	184.35	32.33	5.70	0.000	120.20	248.50
lnopr	35.71	12.77	2.80	0.006	10.38	61.04
lndrywt	–13.64	10.37	–1.32	0.191	–34.22	6.93
lnsfc	2.01	9.73	0.21	0.837	–17.30	21.33
lnmaxfn	–7.88	11.82	–0.67	0.507	–31.33	15.58
_cons	–1200.78	214.41	–5.60	0.000	–1626.23	–775.34

Number of observations = 105
F statistic (5, 99) = 68.77
Probability > F = 0.0000
R-squared = 0.78
Adjusted R-squared = 0.77
RMSE = 22.522

[a] P>|t| = Probability of accepting the null hypothesis (i.e., the coefficient is zero).

The variables in Table A.1 are as follows:

- newTOA is the number of quarters since June 1942 for LPR or MQT
- lnritf is the log of the turbine rotor inlet temperature in degrees F
- lnopr is the log of the overall pressure ratio
- lndrywt is the log of the dry weight of the engine in pounds
- lnsfc is the log of the specific fuel consumption (fuel flow divided by thrust at intermediate rating point)
- lnmaxfn is the log of either (a) maximum thrust if it is an afterburning engine or (b) the thrust at the intermediate rating point.

There is one difference between the TOA formulation shown in Table A.1 and the formulation in the previous studies. The term lnopr is not quite the same. Nelson and Timson (1974) said that their term used to denote the same variable, lnTOTPRS, is the log of the "… product of the maximum dynamic pressure in the flight envelope and the pressure ratio of the engine." We did not have the maximum dynamic pressure for the engines in our sample, so we simply used the pressure ratio.

We can make two important observations about the original delta TOA relationship. First, the specific fuel consumption and maximum thrust terms are not significant with the expanded data sample (compared with the prior studies). Also, the sign on the coefficient for the thrust term (lnmaxfn) is incorrect (the negative sign implies that lower-thrust engines are expected to reach production later than higher-thrust ones). One can better understand this lack of significance by examining in Table A.2 the correlation coefficients for the two variables (specific fuel consumption and maximum thrust) that drop out of the regression.

Notice that some of the independent terms shown in Table A.2 are highly correlated with one another—specifically, the correlation pairs lnritf with lnopr, lnopr with lnmaxfn, and lndrywt with lnmaxfn. It is not appropriate to have such highly correlated terms as independent variables in a regression equation. The high correlation with other variables makes the coefficients for lnsfc and lnfnmax insignificant.

The second observation we can make about the original TOA formulation is that the residual errors are not uniformly distributed. Figure A.1 shows the residual error plotted versus the predicted TOA value. Notice how the residual dispersion expands with larger predicted values.[3]

---

[3] For more statistically inclined readers, the Cook-Weisberg test for heteroscedasticity using fitted values of newTOA shows the following:

Ho: Constant variance

chi2(1) = 12.29

Prob > chi2 = 0.0005

These results indicate a fairly significant problem with heteroscedasticity. See Cook and Weisberg (1982) and "Diagnostics for Heteroscedasticity …," (1983).

Table A.2

Correlation Coefficients for Parameters in Original TOA Formulation

	NewTOA	lnritf	lnopr	lndrywt	lnsfc	lnmaxfn
newTOA	1.0000	—	—	—	—	—
lnritf	0.8427	1.0000	—	—	—	—
lnopr	0.7124	0.8542	1.0000	—	—	—
lndrywt	0.0364	0.2858	0.5411	1.0000	—	—
lnsfc	–0.4660	–0.5702	–0.6875	–0.4014	1.0000	—
lnmaxfn	0.3146	0.5800	0.7326	0.9093	–0.4886	1.0000

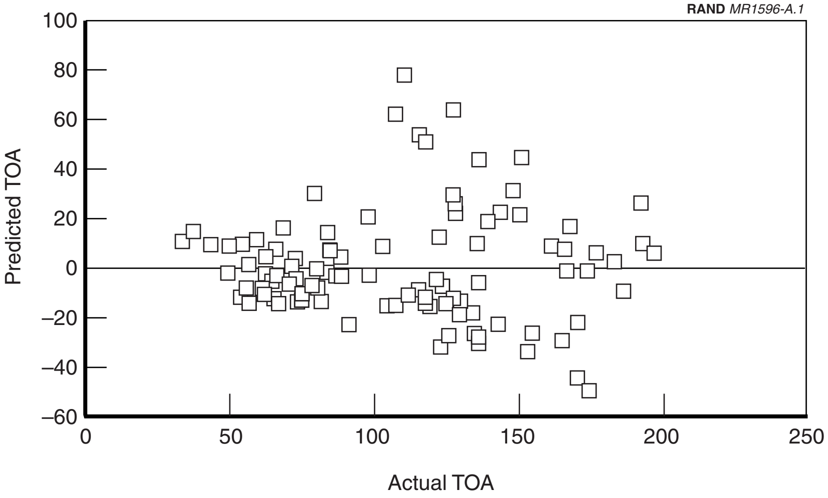

Figure A.1—Residual Versus Predicted Values for TOA Formulation

NEW TOA FORMULATIONS

Based on the observation in the previous section, we attempted to formulate a new TOA metric. We developed two different formulations of a new TOA: one based on all engines (both new and simple derivatives, as defined in Chapter Six) and another based solely on new engines.

New Engine and Derivative Engine TOA

Based on our analysis, we revised the TOA formulation, as shown in Table A.3.

Table A.3

Revised TOA Formulation

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	17.11	4	4.28
Residual	3.58	100	0.04
Total	20.69	104	0.20

lnnewTOA	Coefficient	Standard Error	t-statistic	P>|t|	95% Confidence Interval	
lnritf	3.37	0.41	8.19	0.000	2.55	4.19
lndrywt	–0.15	0.03	–5.89	0.000	–0.20	–0.10
fan	13.36	3.44	3.89	0.000	6.54	20.18
fanxrit	–1.76	0.46	–3.84	0.000	–2.67	–0.85
_cons	–19.66	3.04	–6.47	0.000	–25.68	–13.63

Number of observations = 105
F statistic (4, 100) = 119.54
Probability > F = 0.0000
R-squared = 0.83
Adjusted R-squared = 0.82
RMSE = 0.18918

The variables in Table A.3 are as follows:

- lnnewTOA is the log of newTOA
- lnritf is the log of the turbine rotor inlet temperature in degrees F
- lndrywt is the log of the dry weight of the engine in pounds
- fan is the binary term in which 1= turbofan and 0 = turbojet
- fanxrit is the cross term between fan *x* lnritf.

The lnopr term does not appear in this revised formulation because it was correlated too strongly with lndrywt. This new formulation does not have the same heteroscedatic problem as the one shown in

Table A.1.[4] However, as is evident from the "fan" binary term, the turbojet engines do behave differently. Turbofan engines are forecast to arrive later, all other factors being equal, but the TOA does not have as strong a dependence on lnritf.

To be consistent with our analysis that centers solely on turbofan engines, we arrive at a TOA for fan engines only, as shown in Table A.4.

The term FIS, or "first in series," is a binary term to denote the first engine in a series (1 is true; 0 is false). In other words, when FIS is zero, the engine is a derivative.[5] Note the significantly poorer R-squared, but the RSME remains about the same as compared with

Table A.4

Turbofan-Engine-Only TOA

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	2.11	3	0.70
Residual	1.93	52	0.04
Total	4.04	55	0.07

lnnewTOA	Coefficient	Standard Error	t-statistic	P>|t|	95% Confidence Interval	
lnritf	1.62	0.22	7.213	0.000	1.17	2.07
lndrywt	–0.16	0.05	–3.394	0.001	–0.25	–0.06
FIS	–0.12	0.05	–2.251	0.029	–0.22	–0.01
_cons	–6.25	1.66	–3.754	0.000	–9.59	–2.91

Number of observations = 56
F statistic (3, 52) = 18.87
Probability > F = 0.0000
R-squared = 0.52
Adjusted R-squared = 0.49
RMSE = 0.1929

---

[4] The Cook-Weisberg test for heteroscedasticity using fitted values of lnnewTOA is:

Ho: Constant variance

chi2(1) = 1.66

Prob > chi2 = 0.1980

[5] There was not a significant difference for the coefficients of the other term for derivative engines and first-in-series engines.

the formulation that includes turbojet engines (see Table A.3). However, the new formulation of Table A.4 still has some bias.

Figure A.2 shows predicted TOA values versus the actual TOA values. In a perfect model, all the points would fall on the diagonal line. For this formulation, there is bias toward the middle of the range. The CER slightly overpredicts for older engines and later underpredicts for more recent ones.[6]

This bias between the forecast and actual values could be due to a number of things. One interpretation is that engine technology has matured over time. However, such an explanation seems unlikely. Another interpretation is that a shift has occurred in the development drivers. The traditional technical factors used for military aircraft no longer determine technical risk. For example, if commercial business demands began to dominate engine performance, other technical considerations, such as controlling noise and emissions,

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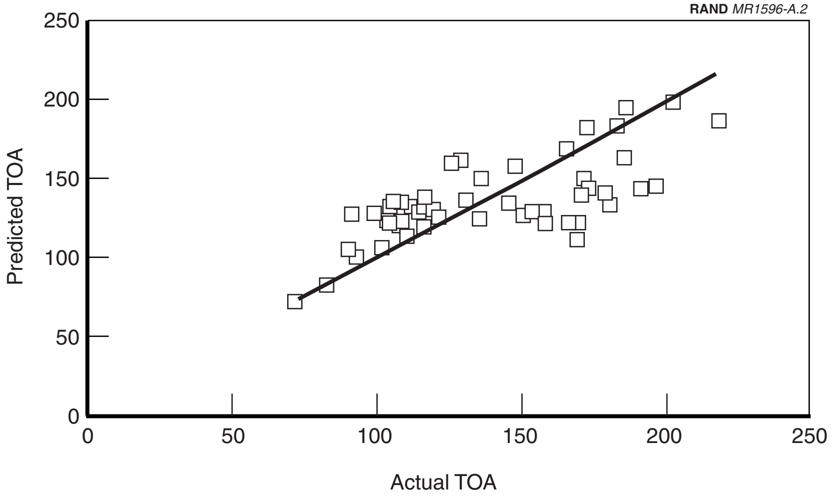

Figure A.2—Predicted TOA Versus Actual TOA

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[6] The two lowest points in the figure are not leveraging. In other words, excluding them from the regression does not change the forecasted values appreciably.

might have also become important. Or, there may have been a shift in strategy in the procurement of new engines. Rather than seeking revolutionary products, the government may have been seeking evolutionary or off-the-shelf solutions.

This discussion leads us to a key question: How well does the new TOA metric correlate with development time? To answer that question, the regression of development time and a new delta TOA are shown in Table A.5. Notice that delTOA6a, the new delta TOA, explains almost *none* of the variance nor is it significant.

New-Engines-Only TOA

Using the definition of a new engine from Chapter Six, we have determined an alternative relationship for TOA, shown in Table A.6. The regression in Table A.7 shows that a delta TOA (based on the formulation from Table A.6) is not significantly correlated with development time.

Table A.5

Revised Delta TOA (Turbofans Only) with Development Time

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	236849.4	1	236849.4
Residual	16134421.1	46	350748.3
Total	16371270.5	47	348324.9

devtime	Coefficient	Standard Error	t-statistic	P>|t|	95% Confidence Interval	
delTOA6a	–2.76	3.36	–0.82	0.415	–9.53	4.00
_cons	1038.27	85.51	12.14	0.000	866.15	1210.38

Number of observations = 48
F statistic (1, 46) = 0.68
Probability > F = 0.4155
R-squared = 0.0145
Adjusted R-squared = -0.0070
RMSE = 592.24

Table A.6

Revised TOA (New Turbofans Only) with Development Time

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	1.75	2	0.87
Residual	0.18	15	0.01
Total	1.92	17	0.11

lnnewTOA	Coefficient	Standard Error	t-statistic	P>|t|	95% Confidence Interval	
lnritf	1.76	0.15	11.65	0.000	1.44	2.08
lndrywt	–0.24	0.04	–5.93	0.000	–0.33	–0.15
_cons	–6.82	1.15	–5.95	0.000	–9.26	–4.38

Number of observations = 18
Probability > F = 0.0000
R-squared = 0.91
Adjusted R-squared = 0.90
RSME = 0.108

The variables in Table A.6 are as follows:

- lnritf is the log of the turbine rotor inlet temperature in degrees F
- lndrywt is the log of the dry weight of the engine in pounds.

Table A.7

Revised Delta TOA (New Turbofans Only) with Development Time

Source	Sum of Squares	Degrees of Freedom	Mean Square
Model	836816.5	1	836816.5
Residual	15534454.0	46	337705.5
Total	16371270.5	47	348324.9

Devtime	Coefficient	Standard Error	t-statistic	P>|t|	95% Confidence Interval	
delTOA12	–4.84	3.08	–1.57	0.122	–11.03	1.35
_cons	1105.66	93.71	11.80	0.000	917.04	1294.27

Number of observations = 48
F statistic (1, 46) = 2.48
Probability > F = 0.1223
R-squared = 0.0511
Adjusted R-squared = 0.0305
RMSE = 581.12

The variables in Table A.7 are as follows:

- devtime is the development time in months
- delTOA12 is the revised delta TOA based on the formulation in Table A.6.

Appendix B

AN OVERVIEW OF MILITARY JET ENGINE HISTORY

This appendix presents a historical overview of military jet engine development in the United States, with a focus on high-performance fighter jet engines. We have divided military jet engine history into four developmental periods, or generations, of jet engines that resulted in major leaps forward in technology and performance: (1) the original centrifugal and axial flow turbojets (first generation); (2) twin spool turbojets, variable stator turbojets, and turbofans (second generation); (3) augmented (afterburning) turbofans (third generation); (4) and supercruise, stealthy "leaky turbojets" (fourth generation).

FIRST-GENERATION JET ENGINE DEVELOPMENT

Initial development of the first practical turbojet aircraft engines began nearly simultaneously in the mid-1930s in Germany and the United Kingdom (UK). Enterprising young engineers and enthusiasts, independent of the established aircraft engine companies, conducted the earliest development work on their own, with little formal financial or technical assistance from either government or industry. Eventually, with the threat of general European war looming closer, European industry and government interest in turbojet engines grew. It was not until World War II was underway, however, that U.S. government and industry committed major resources to the development and production of usable military gas turbine aircraft engines, and the aircraft that they would power.

These early major engine development programs were concentrated in Germany and the UK, with Germany taking the lead. The United States lagged significantly behind Germany and the UK, although the relative lack of U.S. research in jet engine development at that time has been exaggerated (St. Peter, 1999). Nonetheless, jet-powered military aircraft developed in the United States during and immediately after World War II largely depended on British engines and British engine technology.

Although turbine engines had been in industrial use since the nineteenth century, major technical and engineering obstacles prevented their application to aircraft and serious aircraft jet engine development until the mid-1930s. In the late nineteenth century, Englishman Charles Parsons invented a practical industrial steam turbine. It was soon successfully applied to the generation of electricity. By 1900, the British Royal Navy had procured at least two destroyers powered by steam turbines; less than a decade later, commercial ocean liners were equipped routinely with the same type of propulsion. Early in the twentieth century, engineers also began experimenting with gas-powered turbines. One of the most successful early efforts was carried out by Sanford Moss at General Electric (GE), who developed an operational laboratory gas turbine prototype in 1907. Unfortunately, those very early gas turbines were extremely fuel inefficient, using about four times the amount of fuel of an equivalent gas piston engine (Heppenheimer, 1995).

Gas turbines for use on aircraft posed truly daunting technical problems, the most significant of which were obtaining the appropriate lightweight heat-resistant materials and developing adequate compressor efficiency. Another major technical barrier was the need for development of a workable, robust, and reasonably fuel-efficient combustor system to drive the turbine and compressor. For these reasons and others, development efforts for gas turbine aircraft engines languished for decades. In the United States, research at GE and elsewhere focused on the development of turbochargers for conventional piston aircraft engines. These efforts met with great success and resulted in powerful high-altitude piston engines for U.S. Army Air Corps fighters and bombers.

In the UK, theoretical and experimental research on gas turbine engines suitable for aircraft started in the 1920s, led by a few maverick engineers, and continued on through the 1930s on a small scale. As early as 1926, Alan Griffith, a scientist who worked at the Royal Aircraft Establishment at Farnborough, England, developed the concept of a gas turbine based on an axial-flow compressor and turbine arrangement, with the blades acting as airfoils. Griffith envisioned such an engine being used to power a propeller. Some basic research was conducted to determine if this concept would work, but progress on it was slow (Gunston, 1989).

The key early British pioneer, however, was Frank Whittle, a Royal Air Force (RAF) pilot and engineer, who in 1929 began focusing on the concept of a gas turbine engine that used jet propulsion as opposed to one that was used to turn a propeller to power aircraft. Nevertheless, he based his concepts on a centrifugal-flow compressor similar to those used in turbochargers, rather than on the modern axial-flow concept put forward by Griffith.

At this time, Whittle's concept was more feasible than Griffith's given existing technology. In 1935, Whittle obtained venture capital from a private investment-banking firm and began building his first prototype engine on his own time. By 1937, Whittle was conducting successful bench tests of his prototype Whittle Unit engine. By that time, Griffith had become convinced that compressor and turbine technology had made sufficient progress to permit further development of his axial-flow concept. By mid-1937, Sir Henry Tizard, an influential scientist serving in the RAF, recommended government support for development of gas turbine aero engines.

Whittle began receiving small amounts of RAF funding. In June 1939, just a few months before the Nazi invasion of Poland, he demonstrated a more advanced bench prototype for David Pye, the RAF director of scientific research. Pye was extremely impressed, and as a result, the UK government decided to support a major effort for the development of an aircraft jet engine. In July 1939, Whittle's small company called Power Jets received a promise of large-scale government funding for the development of an operational jet engine for flight. A few months after the beginning of the war, Gloster Aircraft won a government contract to develop the aircraft that would use Whittle's new engine. That aircraft became the Gloster Meteor.[1] Finally, a major engine company became impressed with Whittle's work and in June 1939, Rolls-Royce hired Griffith to begin major de-

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[1] See St. Peter (1999) and *A Tribute to a Cambridge Engineering Student …* (1998).

sign work on an axial-flow jet aero engine. Rolls also soon became involved in advanced development of the Whittle engine concepts.

The British government's effort to develop an aircraft jet engine increased substantially after the fall of France in May 1940. By early 1941, Tizard launched an additional program by giving Whittle's and Griffith's research results to de Havilland aircraft, which then was directed to develop its own jet engine and aircraft (the de Havilland Goblin and de Havilland Vampire, respectively). Thus, by 1941, the British government was supporting the development of three military jet engines and two jet fighters.

As impressive as the British program had become, Germany was already far ahead of the UK. The German effort, like the British one, had been initiated by individual entrepreneurs. The first key players were a graduate student in physics at the University of Göttingen, Hans von Ohain, and a chief garage mechanic, Max Hahn. In 1934, von Ohain began design on an axial-flow turbojet engine prototype. He and Hahn built a test article with their own money, but it did not prove to be successful. Von Ohain then approached Ernst Heinkel, a developer of high-performance military aircraft, who became interested in the project. Heinkel hired Von Ohain and Hahn, and began funding their efforts with his company money. By 1939, Von Ohain and other Heinkel engineers had successfully bench tested a usable engine. Heinkel then authorized development of an experimental aircraft for the engine, later called the Heinkel He 178, using company funds. In late August of that year, five days before Hitler invaded Poland, the aircraft made its first successful flight. Although much development work remained, the first jet fighter prototype had now flown, funded entirely by private and corporate money. Around this same time, the German aircraft company Junkers was also attempting to develop an even more advanced turbojet with its company money, but it was lagging behind Heinkel in the development effort. Whittle had only just demonstrated his centrifugal-flow engine to the RAF director of scientific research, and he was just beginning to receive funding to develop a flight-capable jet engine.

In mid-1939, the German Aviation Ministry (or Reichsluftfahrt-Ministerium [RLM]) was supporting a few other jet engine and rocket programs on a small scale, which were based on different technologies. By late in the year, Heinkel and Junkers had both been able to win government financial support for their engine development programs, primarily through the influence of the visionary Brigadier General Ernst Udet, head of the Technical Office of the RLM. At the same time, the RLM let a contract to Messerschmitt to develop a jet fighter design, the Me 262. The RLM also began supporting another jet engine effort at BMW.

Thus, by the end of 1939, only four months into the war, the German government was financing four military jet engine programs: the Junkers Jumo 004, two programs at Heinkel, and the BMW effort. In addition, two jet fighters were under development: the Me 262 and the He 280 (a successor to the He 178). At the time, the British government had launched development of an improved Whittle engine and the Gloster Meteor, both of which would prove to be substantially less capable than their competition coming out of Germany. Griffith was working on his axial-flow concepts at Rolls-Royce but was not making rapid progress.

Meanwhile, in the United States, many companies had begun developing turbojet or turboprop design concepts, including GE, Pratt & Whitney, Lockheed, and Northrop (St. Peter, 1999). In early 1941, however, General Henry "Hap" Arnold, chief of the Army Air Force, along with some GE officials, learned about the British jet engine development programs and the existence of the Whittle engine. Arnold arranged for the transfer of the Whittle technology to GE's turbocharger division at Lynn, Massachusetts, so that the United States could develop a jet fighter quickly. Bell Aircraft received a contract to develop an aircraft, the XP-59A, for the GE-built Whittle engine, which was called the GE 1-A. For the development of future high-technology indigenous engines, many U.S. companies, including GE, Pratt & Whitney, Westinghouse, Lockheed, Northrop, and others, began receiving government research and development (R&D) funding. Unfortunately for the immediate war effort, the XP-59A, like the Gloster Meteor, proved a disappointment due to the shortcomings of the centrifugal-flow concept of the Whittle engine that powered both aircraft.

The Whittle engines could not provide the thrust necessary to make the aircraft competitive with the most advanced piston fighters entering service at the time. The XP-59A first flew in October 1942 with two 1,250-pound-thrust GE 1-A engines. Later variants had the more powerful GE I-16 (later J31) turbojets with 1,650 pounds of thrust. The Meteor, which first flew in March 1943, was powered by two Rolls-Royce–built Whittle W.2B engines with 1,700 pounds of thrust. Advanced piston fighters such as the Republic P-47D and North American P-51D Mustang significantly outclassed both of these heavy and underpowered two-engine aircraft.

De Havilland's axial-flow engine, by comparison, promised twice as much thrust as the Whittle engines, permitting the development of a lighter, higher-performance, single-engine fighter. In September 1943, a de Havilland Vampire prototype powered by a single de Havilland H-1 Goblin turbojet with a thrust rating of 2,700 pounds successfully completed its first flight. Three months earlier, Lockheed received the go-ahead to develop an aircraft using a single de Havilland-built Goblin H-1 engine. The XP-80 Shooting Star first flew in January 1944 powered by this engine, exceeding 500 miles per hour in level flight. But the development program continued to be delayed by engine problems. The Goblin H-1, planned for production in the United States by Allis-Chalmers as the J36, was plagued with problems, and the Air Force began looking around for a substitute.

GE had immediately set out on improving the Whittle-based GE 1-A engine used on the XP-59A. The GE-improved Whittle variants included the I-14, the I-16 (J31), and the I-18, culminating in the dramatically improved and virtually all-new axial-flow 4,000-pound-thrust I-40 (J33) adopted for the XP-80. However, adoption of the GE J33 necessitated major redesign of the XP-80A. The new prototypes did not begin flying until summer 1944. Although the J-33–powered P-80 (later F-80) proved to be a very successful first-generation jet fighter, it completed development too late to see combat during World War II (St. Peter, 1999).[2]

The British war experience with developing jet engines was similar to the experience the United States was having with new jet engine technology. The Gloster Meteor Mk 1, powered by a variant of the Whittle engine developed and manufactured by Rolls-Royce, became operational in 1944 but performed poorly and was retained in the UK for homeland defense. While Allis-Chalmers had experienced prob-

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[2] For a history of XP-80 development, see Knaack (1978).

lems with the XP-80, de Havilland experienced development problems with the axial-flow Goblin engine, and the aircraft did not perform as well as anticipated. In the end, only 174 Vampire F Mk1s were built for the RAF, and they did not become operational until after the war (Gunston, 1989).[3]

Germany, however, was significantly ahead of the UK in the jet engine development effort, and one authority has estimated that Germany had at least a five-year lead in development over the Americans at the beginning of the war (St. Peter, 1999). With their strong lead in 1939 in axial-flow turbo jets, it is not surprising that the Germans proved to be the only combatant to field a successful jet fighter during the war. However, only two of the German jet engine development programs produced reasonably successful operational engines. They were the 2,000-pound-thrust Junkers Jumo 004 engine, two of which powered the Me 262, and the 1,800-pound-thrust BMW 003 engine. Many observers argue that the best and most maneuverable German jet fighter of the war was the Heinkel He 280, powered by the HeS8 that had been developed by von Ohain and others, which first flew in April 1941. The Heinkel He 280 was tested in a mock dogfight against a Focke Wolf FW 190, Germany's best conventional fighter, and beat it badly. But the Heinkel HeS8 engine experienced numerous development problems, and for that and other reasons, the He 280 never entered production.[4]

The very fast but much less maneuverable Me 262, powered by the Jumo 004, first flew in July 1942. The production version of the Jumo 004, however, had to be significantly redesigned to reduce its use of scarce vital war materials such as nickel, chromium, and cobalt. This not only delayed the program but resulted in an unreliable engine. By late 1944, the Me 262 had achieved high-rate production in underground facilities. But by this time, the Allies had near total air superiority and were bombing German industrial facilities and the country's transportation infrastructure around the clock.

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[3] Also see Green and Swanborough (1994); Donald (1999); and Taylor (1995).

[4] For example, see the "Heinkel He 280" link on the Hot Tip Aircraft Web page at www.stud.uni-hannover.de/user/67700/he280.htm and Green and Swanborough (1994).

Nonetheless, the Germans deployed several other very advanced combat aircraft during the last months of the war. Two Jumo 004s powered the world's first operational jet bomber, the Arado Ar 234 Blitz. The Heinkel He 162 Salamander fighter powered by a single 1,800-pound-thrust BMW 003A-1 turbojet became quasi-operational for a very brief period at the end of the war. The rocket-powered Messerschmitt Me 163 Komet fighter also briefly saw combat late in the war. Even more amazing was the Bachem Ba 349A "Natter," a vertically launched rocket fighter tested against allied bombers at the end of the war. Had some of these aircraft, especially the He 280 or Me 262, been operationally available in large numbers earlier in the war, they could have had a major effect on the Allied strategic bombing campaign against Germany. When U.S. Air Force officers, scientists, and engineers visited German R&D facilities after the war, many of them were shocked at how far advanced the Germans were in jet aircraft design compared with the Americans. The U.S. was determined more than ever to develop advanced jet-powered military aircraft. They knew that significant new engine technology would be crucial to that effort.

SECOND-GENERATION JETS REVOLUTIONIZE MILITARY AND COMMERCIAL AIRCRAFT

Three key jet engine technological developments in the 1950s revolutionized aircraft performance: twin spool turbojets, early low- and medium-bypass turbofans or fanjets, and variable compressor technology. These developments led to the realization of supersonic military jet fighters, competitive carrier-based jet fighters, and long-range jet-powered military and commercial transport aircraft.

In the immediate post-War years, GE, Westinghouse, P&W, the Allison Division of General Motors, and Curtiss Wright were considered the leading U.S. turbojet manufacturers, while Rolls-Royce remained dominant among many jet engine manufacturers in the UK. German companies such as Junkers and Heinkel had their facilities severely damaged by the war and were forbidden by treaty to continue developing militarily useful technologies.

During the war, the UK government had required British industry to cooperate and share information in the development of turbojet engines. Using a much different approach, the U.S. government had encouraged competition among firms and discouraged sharing of information. The U.S. approach promoted development of different technical solutions. GE had begun with the basic Whittle technology and improved on it greatly until it had achieved its own indigenous engines, the J33 and J35 turbojets. GE developments had been largely sponsored by the Air Force; GE engines were widely used to power first-generation Air Force fighters and bombers. Westinghouse had a long history of steam turbine development and expertise. During the war, its turbojet development activities were sponsored by the Navy, and most first-generation Navy fighters were powered by Westinghouse engines. Allison initially produced mostly GE-designed engines for the Air Force due to GE's lack of production facilities. With little independent wartime turbojet R&D experience of its own, P&W decided to produce the Rolls-Royce–licensed Nene engine, a very advanced successor to the original Whittle W.2B turbojet. With the German firms in ruins, Rolls-Royce was considered by many in the early post-War period to be the most advanced turbojet manufacturer. P&W Nene-based engines were used on both Navy and Air Force aircraft.[5]

All turbojets during the immediate post-War era suffered from at least four major shortcomings: high fuel consumption, relatively low thrust, sluggish acceleration, and loud noise. These problems greatly complicated the development of naval carrier-based jet fighters, long-range land-based fighters, long-range strategic bombers, and commercial jet airliners. P&W decided that it was at least five years

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[5] Wright Aeronautical, a division of the Curtiss-Wright Corporation, along with P&W, a division of United Aircraft, had been the most important U.S. aero engine manufacturers during World War II. Indeed, by 1940, Curtiss-Wright was the largest U.S. company in the aircraft industry. During the last year and a half of the war, the government officially prohibited Wright Aeronautical and P&W from pursuing jet engine development research in order to force them to concentrate on war production. After the war, Wright received jet R&D contracts, gained access to Westinghouse J34 engine technologies, and built GE J-47 engines. During the Korean War, Wright license produced two British jet engines. The Air Force chose Wright to develop its own higher-thrust J-67 turbojet for the Convair F-102, but cancelled the program because of perceived poor performance by Wright during the Korean War. Wright never recovered from the cancelled business and ceased to be a jet engine prime contractor. Lockheed and Northrop also exited the engine industry soon after the war. Westinghouse also left the industry after producing several engine developments in the 1950s. See Gholz (2000).

behind the other major turbojet companies in R&D expertise and had to achieve a major leap forward in technology to stay competitive in the post-War environment. License-producing Rolls-Royce engines was a dead-end approach, so beginning in 1946, P&W made a major corporate strategic decision to invest substantial amounts of its own funds in new R&D and test facilities to catch up with its competitors.

The focus of P&W's R&D efforts was aimed at solving the two most significant shortcomings of existing turbojets, especially for military use: low thrust and high fuel consumption. The best engines in the early post-War years produced 4,000 to 5,000 pounds of thrust. P&W established the goal of doubling this thrust level by developing a 10,000-pound-thrust engine that also had better fuel efficiency. P&W's corporate leadership focused on the military market but also recognized the possibility of later commercial applications.

Of the five main U.S. jet engine companies, only P&W believed that dramatically increasing the compressor pressure ratio was the way to solve the thrust and fuel efficiency problems. P&W engineers developed the key concept to make the technological leap in this area: the "twin spool" engine (Heppenheimer, 1995; St. Peter, 1999).[6] The concept called for two different sets of compressor and turbine combinations in the same engine. A low-pressure compressor at the front of the engine would be driven by a low-pressure turbine connected by a rotating shaft inside a second rotating shaft. The outer shaft would connect a high-pressure compressor behind the low-pressure compressor to a high-pressure turbine located in front of the low-pressure turbine. This approach promised a substantial increase in the overall efficiency of the compressors and improved performance during engine acceleration and deceleration, while also enhancing fuel efficiency and increasing thrust.

The new P&W engine, designated the J57, first ran on a test stand in 1950 (Heppenheimer, 1995). The J57 proved to be a huge, even revolutionary, advance in axial-flow turbojet technology. It was the first jet engine to develop 10,000 pounds of thrust, double that of most of its contemporaries. Later versions developed up to 18,000

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[6] Gunston (1989) indicates that Rolls-Royce engineers were also examining the concept of dual-spool engines immediately following the end of the war.

pounds of thrust. At the same time, it had nearly twice the fuel efficiency of the most successful German World War II engine, the 2,000-pound-thrust Junkers Jumo 004. The J57 made development of the first true long-range strategic jet bomber possible, the Boeing B-52. It also helped make supersonic flight possible. In May 1953, the North American YF-100 fighter became the first combat aircraft in the world to achieve sustained-level supersonic flight. In addition to the B-52 and the F-100, the J57 powered numerous other Air Force aircraft such as the McDonnell F-101 fighter, the General Dynamics (GD) Convair F-102 fighter, and the Boeing KC-135 aerial tanker. Navy tactical aircraft equipped with this engine included the Vought F8U and the Douglas F4D, F5D, and A3D. The improved J-75, which was based on the same fundamental principles but used more-exotic higher-temperature materials to produce greater thrust, powered the Republic F-105 and Convair General Dynamics F-106 fighters, and other military aircraft.

Finally, the J57 also made the development of successful long-range commercial and military jet transports possible when its commercial version, the JT3, was used to power the Boeing B-707. But to achieve the full potential of this capability, another major innovation was borrowed from the British by P&W and added to the JT3, resulting in the JT3D. This innovation was the development of the low-BPR turbofan or fanjet. Rolls-Royce engineers had been considering bypass jet engines since the end of World War II. These engines have larger low-pressure compressors that permit a portion of the air to be ducted past and around the core of the engine and expelled with the hot jet gas from the core. This feature results in lower specific fuel consumption, higher thrust, and lower noise. The dual-spool configuration is necessary for fanjets because the low-pressure spool and high-pressure spool turn at different speeds. Rolls-Royce developed a low-bypass turbofan called the Conway, which was used on the de Havilland Comet jet commercial transport and entered service in May 1952. Because of the wing-buried installation on the Comet, and on early British jet bombers such as the Vulcan, the engine could not be optimized with a large enough fan for optimal fuel efficiency and transatlantic range (Gunston, 1989).

P&W engineers were initially skeptical about fanjets. GE, however, developed its own successful version of a fanjet based on a slightly different approach—the “aft fan” concept in which the fan is mounted with and behind the turbine near the back of the engine. This concept was successfully bench tested in 1957 as the CJ-805. P&W decided to move ahead with a fanjet when Boeing threatened to go with the GE engine for its new long-range 707s.

P&W engineers successfully modified the standard J57 military turbojet with a larger front-end compressor/fan, turning it into a high-efficiency low-bypass turbofan engine suitable for very-long-range flight. Suddenly P&W had a large advantage over GE because the modification to the J57 was relatively minor, and that engine was already proven to be a highly capable engine. GE's rear-fan engine was just a test article. The Air Force quickly became interested in the P&W JT3D and eventually used the military variant (TF33) for the KC-135 aerial tanker and other aircraft. Besides the Boeing B-707, the JT3D commercial variant powered the competing Douglas DC-8, as well as the Boeing 720. More than 21,000 J57/JT3s were eventually produced well into the 1980s. Most important, the low-bypass turbofan later led to advanced new fighter engines and to high- and very-high-bypass turbofans, which revolutionized commercial transport power plants.

The move toward high-pressure-ratio engines first advocated by P&W soon confronted designers with new difficulties. As pressure ratios increased for optimal efficiency at cruise conditions, problems arose with the design of the compressor operating efficiently at low speeds and especially during acceleration. Under these conditions, airflow patterns over the compressor airfoils were very different than they were under their design conditions, and small disturbances that could cause compressor stall became common. GE made the revolutionary technological breakthroughs that solved this problem by developing variable-geometry compressor systems, which used variable-geometry stators. A row of stators redirects the airflow between each row of rotating compressor blades in the compressor assembly. Variable stators change their angle of attack for different airflow conditions, thus addressing the compressor stall problems. This technological breakthrough led to the development of the famous J79 turbojet engine, made Mach 2 flight possible, and was critical for the development of modern very-high-bypass commercial engines that power today's large airliners.

The GE X24A design concept emerged in response to an Air Force requirement for a high-thrust, fuel-efficient, Mach 2 fighter engine. GE received a study contract; in 1952, the Air Force designated the new engine the J79. Full development began with Air Force funding a year later. The production prototype had its first test run less than a year later, and flight testing began in mid-1955. The J79 was originally slated for use on the Convair General Dynamics B-58, the world's first Mach 2 bomber, and the Lockheed F-104, the world's first Mach 2 fighter. The J79 also powered Navy aircraft, such as the Douglas F4D fighter and the North American A3J carrier-based bomber. Perhaps most important, the J79 powered the world's most important combat aircraft of the 1960s and 1970s, the McDonnell-Douglas F-4 Phantom, used by many foreign countries as well as by both the U.S. Air Force and Navy. About 5,200 F-4 Phantoms were manufactured from 1958 through 1979, more than any other U.S. fighter since the North American F-86 in the 1950s or any other U.S. fighter since.[7]

Thus, the P&W J57 and the GE J79 were clearly the most important and revolutionary jet engines of the 1950s and 1960s. The J57/JT3D, originally developed through industry initiative and with company funds, laid the groundwork for all modern jet engines, made sustained supersonic flight practical for jet fighters, and pioneered the fan jet concept that later led to far-more-advanced fighter and commercial engine concepts. The J79 illustrated the tremendous thrust and speed potential of modern jet engines and demonstrated beyond a doubt the world leadership of the U.S. jet engine industry.

AUGMENTED TURBOFAN ENGINES

By the end of the 1950s, U.S. engine developers began focusing on new military engines that combined unprecedented high-speed capabilities through the use of high thrust-to-weight ratios and afterburners with the efficiency and lower specific fuel consumption resulting from fanjet technology. The performance demands required by the services were high, and the technical challenges were numerous. The first of these engines pushed the edge of the feasible technical and performance envelopes of the era. As a result, several of the

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[7] By 2001, production of the General Dynamics/Lockheed F-16 had reached 4,300 in number and additional sales of the F-16 were likely.

early augmented turbofan programs experienced serious developmental problems. The major technical problems revolved around inlet airflow and compressor stall. There were also problems with reliability and maintainability.

The P&W TF30 was the first operational afterburning turbofan, and so it was a challenging development. P&W had experimented with a duct-burning turbofan in 1956, but the TF30 burned both fan and turbine exhaust air in the same afterburner. The TF30 began development in 1959 in support of what later became the TFX program in 1961. The TFX program, which resulted in the General Dynamics F-111, called for the development of a large supersonic fighter/bomber to meet both Air Force and Navy carrier-borne aircraft requirements. The government selected two airframe and engine finalists in January 1962: General Dynamics/Grumman teamed with P&W and Boeing teamed with GE. Secretary of Defense Robert McNamara overruled the source selection team's choice of Boeing, and in late 1962, the selection team awarded the GD/Grumman/P&W team what was, at the time, the largest aircraft development and production project in history.[8]

The TF30 went through at least 12 years of development and various fixes before its reliability and performance became operationally acceptable, yet all of its problems had not yet been solved. Flight testing by GD of the F-111 with the P&W YTF30 engine began in 1964. From the very beginning, developmental testing showed serious engine problems with compressor stall and catastrophic rotor failure at high speeds. At great expense in money and time, GD, P&W, and the government attempted to solve these problems with several redesigns of the aircraft's engine inlet, but the problems were never totally fixed. The Navy withdrew from the F-111 program in 1968 and went on to develop its own air-superiority fighter, the Grumman F-14 Tomcat. This new Navy fighter also used the TF30 engine. Like the F-111 program, the TF30 experienced serious developmental problems on the F-14 program. The TF30 program had been a pioneering development effort, but its many problems seriously damaged P&W's reputation with both the Air Force and the Navy (St. Peter, 1999).

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[8] For a more detailed discussion of this controversial decision, see Lorell and Levaux (1998).

The TF30 development was followed by a new P&W effort aimed at developing a second-generation high-performance augmented turbofan, the F100. The Air Force requirement called for a major leap in performance capabilities for this engine compared with earlier engines. Simply put, the Air Force asked for a new engine that would approximately double the thrust-to-weight ratios of previous generation engines then in use, such as the J79.[9] The F100 program was technically very demanding and high risk. Not surprisingly, it resulted in another major controversy and in a significant change in the way the Air Force approached development and procurement of fighter engines. The F100 development experience led the Air Force to be much more receptive to supporting simultaneous competing engine development and production programs, as the service had routinely done in the 1940s and 1950s.

The story of the F100 began after the Navy withdrew from the F-111 program and after the formulation of requirements for a new Navy fighter (the VFX, ultimately the Grumman F-14), and for a new Air Force air-superiority fighter (the F-X, which became the McDonnell-Douglas F-15). The Department of Defense mandated that both services use the same engine core for their respective fighters.

The Air Force took the lead in the early developmental stages of the F100 program because the Air Force Aero Propulsion Laboratory had taken the lead on the Advanced Turbine Engine Gas Generator (ATEGG) program. Like the current IHPTET program, ATEGG brought together advanced prototype components from P&W, GE, and Allison to see how they would work together as a system. The Advanced Technology Engine program for the FX and VFX, led by the Air Force, grew out of this effort. In 1968, P&W, GE, and Allison submitted competitive design proposals. The Air Force selected P&W and GE to continue the competition by building and demonstrating two prototype engines over an 18-month period. In early 1970, the Air Force selected P&W to develop its JTF-22 design, which later became the F100 turbofan. Ironically, P&W won the bid for the JTF-22 work in part because of its demonstration of a greater understanding of engine/inlet compatibility phenomena, which was acquired in

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[9] St. Peter (1999) puts the thrust-to-weight ratio of the J79 at 4.67:1, while the TF30, the first-generation augmented turbofan, is rated at 5.26:1. The F100 is listed with a thrust-to-weight ratio of 7.7:1.

part through years of problems with the TF30 on the F-111 and the F-14.[10]

The F100 was an extremely innovative engine that pushed the boundaries of contemporary technology, especially in the area of exotic high-temperature materials. A tight Air Force schedule and budget left little room for dealing with the inevitable technical problems, schedule slippage, and cost growth. In June 1971, the Navy pulled out of the program because of continuing technical development problems, dramatically increasing the program costs for the Air Force. Not only did development problems continue through full-scale development and flight testing, but the engine went into production before development was completed. Fixes done under government-funded Component Improvement Programs continued after the engine entered service with the F-15 in late 1974. The engine was extremely powerful and capable but continued to experience severe operational and reliability problems.

The F100 engine was so powerful and the F-15 so maneuverable that pilots began pushing the aircraft to the edge of the performance envelope in ways that stressed the engine far more than had been anticipated. These stresses resulted in much worse reliability and maintenance problems than were originally expected. In addition, new heavy-maneuvering air-to-air combat tactics developed by Air Force pilots revealed another problem: compressor stall caused by strong dynamic airflow distortion in the engine inlet. Severe compressor stall could lead to engine flame out, requiring the pilot to restart the engine in flight. This problem caused particular concern because the F100 was planned for use on the single-engine General Dynamics (now Lockheed) F-16 as well as on the dual-engine F-15. The compressor stall problem also contributed to another major shortcoming—turbine blade fatigue and failures that had the potential of destroying the aircraft in flight. To avoid potentially catastrophic accidents, performance limitations were placed on pilots, and mechanics had to de-rate the engine.

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[10] There are several studies of the development of the F100 and the resulting “Great Engine War” between P&W and GE. They include Camm (1993); Ogg (1987); Drewes (1987); Kennedy (1985); and Mayes (1988).

As these problems became evident, relations deteriorated between P&W management and the Air Force. The Air Force wanted P&W to fix the engine under the existing contract. P&W argued that it had delivered an engine that met the original performance specifications. The problem, according to P&W, was that the Air Force began operating the engine in a much more demanding environment than had originally been specified. Therefore, P&W argued that the Air Force should provide additional developmental money to fix the problems.

The many problems with the F100 led the Air Force to become increasingly interested in funding an alternative engine development and production program for both the F-15 and the F-16. The obvious source for competition was GE. GE's entry into the Advanced Technology Engine competition had been its F101 design.[11] Learning from the F100 development problems, GE decided to assume less technological performance risk on its F101 and focus more on reliability and maintainability. GE finally received government funding in 1972 to complete the F101 development as an afterburning turbofan to power the North American Rockwell B-1 bomber. In 1979, the Air Force was able to acquire funding to support further development of the F101 as a possible alternative to the P&W F100.

The Air Force had originally viewed its support of the F101 primarily as a ploy to force P&W to be more responsive to fixing the F100 problems. However, Congress soon entered the fray and mandated that the Air Force and Navy fund full competitive engine programs for alternatives to both the Air Force F100 and the Navy's TF30. By 1980, this had been formalized as the Alternate Fighter Engine program. GE entered into the competition its F110 turbofan, an outgrowth of its F101 effort, and P&W went ahead with its improved engine, the F100-220. Between 1984 and 1989, the Air Force pit GE against P&W for orders for new engines for the F-16, making for an intense annual competition. Each year, the engine buy was split between the two companies, but the percentage shares could vary widely from year to year. Yet, at the end of the six years of procure-

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[11] After losing the FX competition, GE moved ahead with further development of the engine using its own money, and teamed with Northrop on the YF-17 Lightweight Fighter program in competition with the General Dynamics/P&W YF-16 team.

ment competition, each contractor had ended up receiving almost exactly half of the total overall orders.

Most studies find little or no evidence that the Air Force enjoyed a significant net savings in total R&D and procurement spending as a result of this competition. On the other hand, it is widely believed that the Air Force acquired better-performing, more-reliable, and more-maintainable engines from more-responsive contractors.

Meanwhile, GE had also moved ahead with and developed the F404 low-bypass turbofan (sometimes called a “leaky turbojet”) out of its J101 work for the Navy’s McDonnell Douglas/Northrop (now Boeing) F/A-18, the developmental outcome of the YF-17. This was intended to be a relatively simple and reliable engine, in the same thrust class as the J79 but with half the weight and far fewer parts. Interestingly, although the Navy was pleased with this engine, the Navy designated P&W as a second source to ensure the possibility of competition. The Navy leadership also noted that of all the U.S. suppliers only P&W and GE were capable of designing and manufacturing advanced jet fighter engines like the F110 and F100 (Dabney and Hirschberg, 1998).

Thus, the era of the augmented turbofan was a stormy period of dramatic increases in engine capability in which P&W pushed the bounds of technology and skirted with failure, while GE benefited from traveling a slightly more conservative route. At the end of the period, the quasi-institutionalized competition between the two remaining key contractors during the “Great Engine War” was viewed by many in the services as being critical to obtaining reliable high-performance military engines.

SUPERCRUISE AND STEALTH

In the early 1980s, the Air Force and Navy formally began developing requirements for next-generation fighters to replace the F-15 and the F-14 and the engines that powered them.[12] The Navy eventually dropped out of this joint effort, later developing its own new fighter,

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[12] This section is based primarily on Hirschberg (1997) and Aronstein, Hirschberg, and Piccirillo (1998).

the F/A-18E/F, powered by the GE F414, a derivative of the F404. The Air Force continued to develop the Advanced Tactical Fighter (ATF) program, which resulted in the F-22 Raptor fighter. The key new performance requirements imposed on the engine developers were supercruise (sustained supersonic capability without afterburner), stealth or LO characteristics, thrust vectoring, short take-off and landing capabilities, high reliability, and low unit cost.

Once again, the primary competitors for the engine business were P&W and GE. Ironically, it can be argued that P&W and GE switched strategies compared with the strategies used previously in the F100 versus F101/110 "Great Engine War" competition. In view of the painful developmental problems that had plagued both the TF30 and F100 programs and the resulting loss of business due to the Air Force's encouragement of GE's reentering the competition, P&W management seemed to have shifted to a strategy of emphasizing somewhat-lower-risk technology and high reliability to win the new engine competition. Yet GE had lost the previous initial FX/VFX competition to P&W in part because of the perceived technological virtuosity of the P&W design. GE was then forced to struggle for more than ten years to reenter the high-end fighter engine market, which it finally did by stressing the reliability and simplicity of its F110 and F404 engines as compared with P&W's problem-prone engines. This time, GE management was determined to win the initial competition and seemed to have concluded that it could be done by adopting P&W's earlier strategy of demonstrating very high performance and unparalleled technological sophistication.

Similar to the earlier Advanced Technology Engine effort that preceded the F100 engine program, a series of government-sponsored component demonstration and concept development programs preceded the development of prototype competitor engines for the ATF. These included such efforts as the Advanced Technology Engine Studies (ATES) program led by the Navy and the Aircraft Propulsion Subsystem Integration program that included development of the Joint Technology Demonstration Engine (JTDE).

In June 1981, the Air Force issued a formal Request for Information to industry for the ATF engine. P&W proposed its ATES design, which drew heavily on its work conducted under the ATEGG and JTDE programs. This was a very-low-bypass turbofan (or leaky turbojet) with counter-rotating spools. GE's ATES efforts examined a series of different design approaches, including variable-cycle engines.

ATES was followed by the Propulsion Assessment for Tactical Systems studies, which teamed the competing engine developers with the competing airframe integrators to conduct more-advanced design studies. During this period, GE decided to adopt a variable-cycle engine concept, which had been demonstrated in various advanced technology programs. In 1984, GE also demonstrated and adopted another novel technical approach: a counter-rotating vaneless interface between the high-pressure turbines (HPTs) and low-pressure turbines (LPTs).

In September 1983, GE and Pratt were awarded contracts to develop prototype ground-test engines to demonstrate the technical capability to develop supercruise, two-dimensional nozzles, and 30,000 pounds of thrust for the new ATF engine. These demonstrator prototypes did not have to meet the weight requirements necessary for flight testing. After a little more than four years, government officials originally planned to select one design to enter into a six-year, full-scale development program, during which flight testing and development would occur.

P&W's XF119 ground demonstrator engine focused on technical issues such as reducing the number of compressor stages in order to lower costs and weight and increase reliability. GE's XF120 ground demonstrator engine moved ahead using the more complex variable-cycle engine concept with the vaneless HPT-LPT interface. The XF120 was also a very-low-bypass leaky turbojet but used a variable-bypass system based on a fairly complex double-bypass concept. Both engine designs employed counter-rotating spools.

In the mid-1980s, several changes implemented by the government and the airframe prime contractors had a major impact on the engine program. In 1985, the Air Force lowered the production unit price target and applied more stringent LO requirements to the ATF engine. More important, in mid-1986 the Air Force decided that the engine contractors must flight test their demonstrator engines before final down-select and the beginning of Engineering and Manufacturing Development (EMD), formerly called Full Scale Development. This meant redesigning the demonstrator engines to flight test the weight standards. This requirement was made more complex when, in 1987, teams from the two primary airframe contractors—GE and P&W—concluded from their extensive design trade studies that a more powerful engine with 35,000 pounds of thrust would be needed.

GE and P&W were permitted to make their own decisions on how much new technology and what capabilities they would demonstrate in their flight-test engines and how much new technology and what capabilities they would demonstrate on ground tests. GE again chose a higher-risk approach than P&W did by choosing to demonstrate more capability in its flight-test demonstrator. Again, the strategy was to win in the final selection by demonstrating greater performance during the flight tests.

P&W's YF119 design for flight demonstration was only slightly different from its XF119 design for ground testing and could not meet the new higher thrust and other requirements in a flight demonstration. GE's YF120 engine, by comparison, was far closer to its proposed EMD design baseline. As a result of these two different approaches, both the Lockheed/GD/Boeing YF-22 and the Northrop/McDonnell-Douglas YF-23 ATF demonstrator aircraft showed higher performance levels with the GE flight demonstration engine than when equipped with the P&W flight demonstration engine. However, the Air Force did not consider this demonstration to be a performance "fly-off" but rather a demonstration of the technical and management capability needed to meet the program objectives during EMD with the least technical risk and the lowest cost.

In April 1991, Secretary of the Air Force Donald Rice announced the selection of the Lockheed team and the P&W engine to proceed into EMD for the new ATF. It appears that Lockheed and P&W were selected on the grounds that their proposals represented lower technical risk and lower cost. GE's variable-cycle approach and vaneless HPT-LPT interface concepts were perceived as new technical approaches that were less than fully proven and complex, and that increased technical risk. P&W successfully portrayed its engine as being more conservative technically, less complex, and, based on incremental improvements, still fully capable of eventually meeting all engine performance requirements at lower risk and cost.

The P&W F119-PW-100 production prototype first flew in 1997. The engine appeared to be experiencing relatively few technical difficulties during the F-22 EMD flight test program, especially in comparison with the F100 and TF30 programs. According to one source, the F119-PW-100 performed “without fault” during the first 500 hours of flight testing on two F-22 EMD prototypes (“F119 Engine Takes F-22 Raptor …,” n.d.). Apparently, Pratt & Whitney had learned its lesson and had been wise in adopting a slightly more conservative technical approach.

Selection of the F119 for the F-22 and successful initial development of the F119 made it a likely candidate for other fighter programs. In spring 1995, Boeing, Lockheed Martin, and McDonnell Douglas, the three contractors that had teams competing during the concept-development and risk-reduction phase of the Joint Strike Fighter (JSF) program, all selected a derivative of the F119 as the engine to power their JSF designs.[13] Key performance requirements were very high reliability for the single-engine Navy JSF variant and sufficient nonaugmented thrust for the short takeoff and vertical landing (STOVL) JSF variant. All three contractor teams decided to start with the F119-PW-100 core and tailor the nozzle, fan, controls, and other features for each variant. The Boeing and Lockheed designs required redesigned fans and low-pressure turbines. At the time, it became clear that the JSF F119 program would become a fairly significant development effort.

With P&W supplying the engine for both the F-22 and all the JSF prime contractor contenders, not to mention all F-15s and a good number of F-16s, concerns grew about the need to provide greater competition and continue support for GE, the country’s sole second source for high-performance fighter engines. In the summer of 1995, Congress directed the JSF Joint Program Office to pursue a second engine source to maintain engine competition during production in the JSF program, as had existed in the 1980s with the F-16 “Great Engine War.” In late November 1995, initial development contracts were awarded to P&W for an F119 derivative and to a GE/Allison team for design studies for the YF120 and F110 variants for the JSF.

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[13] The tri-service international JSF program is intended to replace U.S. Air Force F-16s and A-10s, U.S. Marine Corps AV-8Bs, and British Royal Navy and Royal Air Force Harriers, and in addition augment U.S. Navy F/A-18E/Fs.

In early 1997, P&W received an EMD contract which, when added to earlier JSF engine contract money, amounted to a nearly $1 billion development effort. By that time, GE, Boeing, and Lockheed had settled on the YF120 as the baseline for development of a second engine for the JSF in what had now become the Alternate Engine Program (AEP).[14] Rolls-Royce also now teamed with GE, mainly because of the British firm's acquisition of Allison. Rolls-Royce's share of the YF120 Advanced Technology Engine core development effort stands at 25 percent.[15]

The GE alternative engine is not expected to be available for competition with the P&W engine until the production of JSF Lot 7 commences in 2013. However, Congress has increased funding for the AEP in several annual budgets, and it is possible the GE engine could be available for procurement competition by 2010, or very early in the planned JSF production effort.

The P&W and GE engine variants for JSF are expected to benefit from the ongoing research efforts taking place in the IHPTET program. Initiated in 1988, IHPTET is another ambitious government/industry technology development and demonstration program, which includes the continuation of some earlier efforts mentioned earlier in this appendix. For example, in the interim between the YF120's loss in the ATF competition and its entrance into the AEP for the JSF, the Air Force continued to work with GE through the IHPTET program to mature the YF120's advanced technologies. IHPTET's flagship goal is to double the thrust-to-weight ratio of military turbofans while reducing production and maintenance costs by 35 percent by 2003.[16]

IHPTET, which is half funded by industry and half funded by government, is expected to eventually make possible the development of more-reliable next-generation engines with dramatically higher

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[14] By that time, McDonnell Douglas had been eliminated from the competition.

[15] In addition, Rolls-Royce also plays a significant role in other aspects of the JSF propulsion system that are unassociated with the AEP. For example, Rolls is developing the lift fan mechanism for the Lockheed STOVL design and is developing nozzles and various other parts for the Boeing STOVL design. These efforts are contractor-furnished equipment outside of the government-furnished equipment P&W program and the government-furnished equipment AEP.

[16] See "Integrated High Performance Turbine Engine Technology..." (2001).

thrust. This development continues the tradition of U.S. leadership in development of gas turbine combat aircraft engines, established definitively in the 1950s with the J57 and continuing on to this day.

Appendix C

AIRCRAFT TURBINE ENGINE DEVELOPMENT

The propulsion system of an aircraft, military or commercial, has always been considered a major aircraft subsystem. As performance requirements become more demanding, and as technology evolves, the design and integration of these systems has become more and more complex, posing unique technical and integration challenges to the designer and manufacturer. This is especially true in military aircraft, where ever-increasing tactical mission requirements and an early sustained focus on affordability has driven the prudent development and application of new technologies to achieve those goals.

The U.S. government has been developing aircraft engines for military applications since the 1940s. Since those first developments, increasingly more-demanding missions and performance requirements have driven continual advances, not only in engine technology itself but also in the tools used to develop and apply that technology to new systems. The progressive increase in thrust-to-weight ratio is only one indication of the significant strides made in engine technology over time.[1] This particular leap in capability is due, in large part, to the increased thrust and decreased weight achieved through the application of lightweight, high-temperature materials, as well as the more complex component geometries enabled by advances in design and manufacturing technologies.

Development of these technically complex systems for the military are governed by the Federal Acquisition Regulation and the DoD's

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[1] The trends in thrust-to-weight ratio are depicted in Figure 2.3.

5000 series instructions.[2] These define program phasing, team structure, internal and external review processes, and the associated tollgates or milestones required to periodically release funding. These guidelines also help ensure that critical performance and cost parameters are met, both at the weapon system and major subsystem level. Due to the extensive level of expertise required in each distinct technology area, aircraft and engine development are usually conducted under separate contracts with different suppliers. However, the extensive level of integration of the propulsion system with the aircraft in today's weapon system platforms, coupled with program-level affordability goals, yields a very closely linked, concurrent development process.

Affordability has become a critical component in the effort to maintain a viable development and production base for military aircraft. Controlling the development and production costs of these technologically advanced tactical engines, while still addressing the system's long-term performance reliability and durability needs, poses a significant challenge. Well-managed, prudently applied technology can result in significant savings during the costly development and production phases, as well as efficiencies that yield significant dividends over the life of the weapon system.

The discussion that follows provides the reader with a fundamental understanding of the military engine development process, its complexities, its evolution, and a summary of the factors likely to influence future military engine development programs.

DERIVATIVE ENGINE DEVELOPMENT

In some cases, when an aircraft is being designed or upgraded, an engine that has already been fully developed for another aircraft (military or civilian) can be directly applied to the new platform as an "off-the-shelf" item. While off-the-shelf engines may still require aircraft-specific inlet or nozzle design and integration and may require military qualification, the costs associated with adapting these

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[2] The key documents in the DoD's new 5000 series are "The Defense Acquisition System" (2001); "Operations of the Defense Acquisition Systems" (2001); and "Mandatory Procedures for Major Defense Acquisition Programs …" (2001).

engines can be relatively minor. At the other extreme, developing an aircraft engine from scratch (referred to as a “new centerline”) can cost billions of dollars. A common intermediate solution is to develop a “derivative” engine.

A derivative development starts with an existing engine, and changes are made to components and controls in order to design an engine that meets the new requirements. In some cases, derivative engines are simply “growth”[3] versions of the original engine intended for use in the same aircraft to accommodate increased mission requirements or compensate for increasing aircraft weight. In other cases, derivative engines may be so different from their original engines that they seem almost incomparable. Most derivative engines are built around a previously designed engine’s core and may include other existing components as well. While engine cores are often a relatively small part of the entire engine, they tend to be expensive to design and build due to their high operating temperatures, pressures and stresses, the wide range of operating conditions over which they must smoothly function, and other factors. However, in many instances, significantly different engines have successfully used the same or similar cores. Engine manufacturers can save development funds and reduce risk by building a new engine around an existing core.

A derivative engine is one that uses integrated sets of components (normally a full core at a minimum, and often other components as well) from existing engines. Simply incorporating the engine design principles and practices used in previous development programs does not constitute a derivative development; both new centerline and derivative developments will exploit proven design practices and principles whenever possible and wherever appropriate. Similarly, using individual components from other engines does not constitute a derivative engine, in that much of the development effort and cost go into the matching and integration of components.

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[3] A “growth” engine is an enhanced-performance version of an existing engine, not necessarily a physically larger engine.

ACTIVITIES AND PHASES OF A WEAPON SYSTEMS DEVELOPMENT PROGRAM

The DoD conducts research and development in accordance with DoD Instruction 5000.2, January 4, 2001.[4] This instruction provides a formally defined process and a structured, logical, and cost-effective approach to the development of complex weapon systems. This process applies to development at the weapon-system level and transfers directly to the closely linked development activities at the major-subsystem (i.e., engine) level. Figure C.1 depicts the activities and phases of the acquisition process. A description of the three major activities that make up the DoD 5000 Acquisition Model (Pre-System Acquisition, System Acquisition, and Sustainment) and the phases within those activities are discussed next.[5]

RAND *MR1596-C.1*

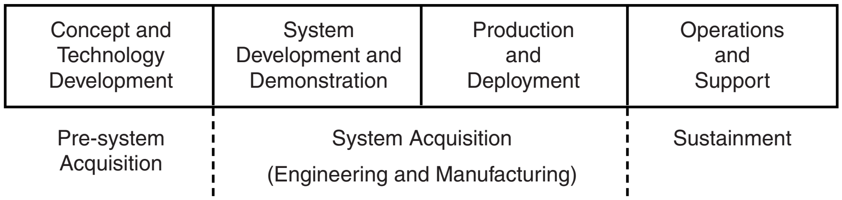

Figure C.1—The DoD 5000 Acquisition Model

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[4] This instruction is continually modified to adapt to the needs of the defense acquisition environment. The most recent release of this document is available at www.acq.osd.mil.

[5] The most recent revision of DoD Instruction 5000.2 was the basis for this discussion of the acquisition process. Prior programs were developed under the earlier, five-phase acquisition model, which consisted of: Concept Exploration, Program Definition and Risk Reduction, Engineering and Manufacturing Development, Production and Fielding/Deployment, and Operational Support. The recently revised acquisition model reflects a stronger tie to Science and Technology programs in the early stages of development, a commitment to production at low-rate initial production, and the flexibility for a program to enter the development process at the appropriate point, based on technical complexity and design maturity.

Pre-System Acquisition

The Pre-System Acquisition activity has three phases: Concept and Technology Development, Concept Exploration, and Advanced Component Development. During this period, government/industry teams explore various alternatives to fulfilling a previously established military mission requirement. The teams work to understand the cost, performance, effectiveness, and risk associated with each of the alternatives identified. Based on these results, the alternatives are refined, preliminary system specifications are outlined, and mission needs are translated into more specific operational requirements. Applicable technologies are then examined, and proposed solutions/design approaches are narrowed. Initial engineering design work may be conducted in this phase to support prototyping or support limited demonstrations in an effort to reduce risk, assess the adequacy of existing technologies, identify additional technological needs, and evaluate the relative effectiveness of and further refine proposed design alternatives.

In the case of military engine development, extensive core design work is done at this point. Individual engine components (fan, compressor, combustor, turbine, augmentor) are designed, built, and tested on rigs to demonstrate their functionality. Control systems are designed to enable the individual components to function together as a whole engine. Full-scale engine functionality is also demonstrated.[6]

Systems Acquisition

At this point, the weapon system development program gains approval to enter the Systems Acquisition activity. The first part of Systems Acquisition is the System Development and Demonstration phase, where the most promising design approach is fully developed.

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[6] In the earlier acquisition model, most of the early design and integration work, technology transitioning from concept exploration, and prototyping were done during the program development and risk reduction phase. Historical data show the typical duration of the program development and risk reduction phase to be two to four years, depending on system complexity. In an attempt to reduce risk and achieve higher confidence before commitment of EMD funds, the duration of the Program Definition and Risk Reduction phase has increased over time.

Detailed engineering design and test work is completed, hardware and software configurations are refined, full system capabilities are demonstrated, performance analysis is completed, and the manufacturing process is validated. The Production and Deployment phase is the next phase of System Acquisition. During this phase, the weapon system enters Low-Rate Initial Production and eventually gains approval for Full-Rate Production.

The engine transitions with the aircraft into the Production and Deployment phase. This phase includes any evolutionary acquisition efforts, such as block upgrades to deployed systems.

Sustainment

At this point, the weapon system program transitions into the Sustainment activity, the final segment of the revised acquisition model. During this period, the program must provide everything necessary to maintain the readiness and operational capabilities of the deployed system. Sustainment also includes demilitarization and disposal of the system at the end of its useful life.

A HISTORY OF THE ENGINE TESTING AND QUALIFICATION PROCESS

In the earlier years of aircraft turbine engine development, the development phase began with the engineering design work necessary to produce a first engine to test (FETT). After some basic test work to demonstrate limited functionality, the engine was released for flight test by approval of the Preliminary Flight Release (PFR) milestone. The development program culminated in the successful completion of a 150-hour Model Qualification Test. The MQT was designed to exercise the engine at sustained operating conditions, focusing on the creep (stretching) characteristics of the materials used in engine design at the time. The MQT did little to address durability problems caused by cyclic (recurrent/repeated) forces acting on engine components.

Upon successful completion of the MQT, the engine design was released for production. Any deficiencies in performance or durability not initially identified during the formal development program were culled out through operation in the field. Correction of these deficiencies relied on a robust post-development Component Improvement Program, the role of which is to enhance reliability or durability or to regain lost performance in an already deployed system. However, the full redesign cycle, from initial identification of a problem to the commitment of funds for the engineering work (Component Improvement Program) to correct it, and the eventual development and incorporation of that correction, could be extensive, depending on the magnitude of the problem. This caused some systems to suffer long periods of inadequate operational performance or availability while these steps were taken.

With ever-increasing performance and durability requirements and more-aggressive mission profiles, as well as the advent of more sophisticated design and qualification tools, the philosophical approach to aircraft turbine engine design has evolved significantly over the years. As material composition of engines migrated from the more conventional materials into more-advanced materials such as super alloys, and the engine community began to understand the implications of cyclic fatigue on engine durability, the government significantly increased its qualification requirements for military aircraft turbine engines. The late 1960s marked a significant change in the military engine development and qualification process. It was at this point that the MQT milestone was replaced with Initial Service Release (ISR) and Operational Capability Release (OCR) milestones. The ISR milestone was to provide assurance that critical system specification requirements had been met and that the engine was producible. The engine then moved into extended mission-based durability testing to provide confidence that the system would achieve full specification life and was ready for full-rate production at OCR.[7]

TEST PROCESS MILESTONES

As mentioned earlier, today's military engine development programs follow the same acquisition model as that of a military aircraft. The military engine, today more than ever, is a highly integrated aircraft

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[7] Cote and Lilly (1985) provide more specific background on a number of aircraft turbine engine development programs conducted in 1985.

subsystem. For this reason, engine and aircraft developments are very closely linked. First flight and Initial Operational Capability (IOC) milestones for the weapon system must be assigned in concert with the engine's corresponding FETT, PFR, ISR, and OCR milestones to ensure a fully integrated operational system at each checkpoint. For example, the engine's ability to meet a given FETT date, and eventually the PFR date, is driven by its level of design maturity when entering into development, the availability of raw materials, the length of the hardware fabrication cycle, and the amount of hardware and software integration required. The engine FETT and PFR milestones directly influence the weapon system's ability to achieve its first-flight milestone. Similarly, the engine ISR milestone, which demonstrates engine performance, and the OCR milestone, which demonstrates specification life requirements, are both critical factors in the eventual IOC of the weapon system.

In agreeing on development program milestone dates, an obvious consideration is the testing required for approval of each milestone and the resources—the hardware assets, available time, and funding—to achieve it. It is a straightforward exercise simply to impose milestone dates on the engine program based on an end date defined at the weapon-system level. A much greater challenge is negotiating a balance between the cost and scheduling pressures with the engineering and test work required to produce a high-integrity system. Therefore, if an aircraft must be operational by a given date or if funding is constrained, engine design may have to be simplified to meet the necessary milestones.[8] Conversely, if meeting established specification requirements is paramount, difficulties can and will delay deployment of the weapon system.

EFFECT OF DESIGN AND TESTING TOOLS ON DEVELOPMENT COST AND TIME

The advent of more-sophisticated design and testing tools has both simplified and complicated the engine testing and qualification pro-

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[8] In this instance, block upgrade approaches are often used, not just for the engine, but for other major subsystems as well. This is a perfectly acceptable approach, as long as the weapon system is able to meet threshold cost, schedule, and performance requirements with the relaxed subsystem requirements.

cess. Tools such as CAD/CAM, finite element models to evaluate internal stresses in solid components, CFD models to optimize internal aerodynamics and combustion processes, and many others enable engineers to complete many more design iterations before reaching an optimal design solution. Sophisticated design and test tools also enable engineers to react much more quickly when testing yields an unexpected result, and system deficiencies are identified through modeling and simulation rather than during operation in the field. However, because the predictive ability of these tools is so much better, more technical problems are identified earlier in the process. Resolution of these design problems, which once occurred post-development, absorbs some of the development time and cost saved by the efficiency of the tools. A more significant portion of the time savings, however, is absorbed by the more complex technology required to meet ever-increasing demands for performance and durability. As a result, these tools help produce a much better performing, more reliable, and more predictable product for the operator and maintainer but do not necessarily save time or money during the development phase.

A NOTIONAL DEVELOPMENT TEST PLAN

For purposes of this discussion, a notional development test plan[9] for a military aircraft turbine engine entering development at a low level of technology risk is depicted in Figure C.2. Obviously, this is meant only as an example of what a typical, straightforward engine development plan might include. It is not meant to be a generic template for all programs to follow. Formulation of an engine development test plan is a complex, program-specific process, and plans

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[9] Skira (1999) provides a detailed discussion of notional engine test plans and what can be done to improve the cost and schedule resources required to qualify an engine. Using a weighted average approach, Skira first formulates a “baseline” notional engine development program that spans ten years, requires 14 test assets, and 11,000 hours of engine test. Upon incorporating the benefits of advanced design tools, materials, and processes, his method yields a significantly streamlined program, spanning 5.5 years, and using nine test assets and 7,550 engine test hours. The notional plan shown in this report is meant to familiarize one with what a more typical program may require.

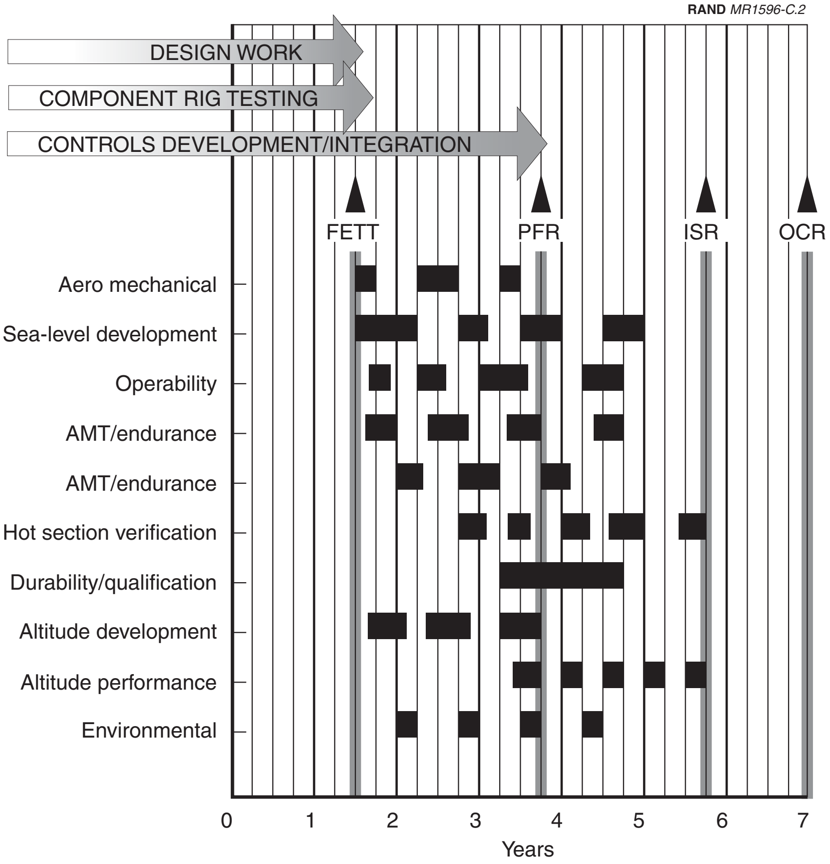

Figure C.2—Notional Engine Development Test Plan

must be tailored to meet individual cost, schedule, and performance requirements to ensure development of a high-integrity operational system.

This notional test plan shown in Figure C.2 spans seven years from contract authorization through OCR and includes five component rigs, 12 development engines, and approximately 10,000 ground-test hours. For this illustration, the component rigs transitioned from the Program Definition and Risk Reduction phase are available to design engineers for gathering component-specific data in support of FETT.

The 12 development engines are each built to accommodate the unique requirements of a particular type of test. This plan does not account for any spare hardware assets, which can be a significant contributor to development costs. The number of flight test engines (not included here) would be determined by the needs of the aircraft flight test team. Ground-test engines are typically not transferred to the flight test program due to specialized instrumentation needs and the unquantifiable wear accumulated during ground test.

Component testing is conducted first in the test program and is essentially used as a risk reduction measure to indicate whether a proposed design is feasible. Component testing is conducted on a rig, or “slave” engine, to evaluate and verify the individual component’s performance and mechanical integrity and to assess material stresses and vibration modes. Typically, the fan, compressors, turbines, and combustor are tested on a rig, while an augmentor is tested on a slave engine.

The 12 development engines contained in this notional plan are allocated for different testing purposes. Aeromechanical testing is used to evaluate the stresses and vibration modes of engine turbo machinery (fan, compressor, and turbine blades) and the functionality of other components, such as the combustor, augmentor, and nozzle. Initial aeromechanical assessments are conducted on a rig, then in an expressly instrumented engine in a sea-level test cell, and then under worst-case conditions in an altitude test cell. The instrumentation takes static and dynamic measurements of rotor speeds, inlet conditions, pressures, temperatures, and airflow to evaluate both static and dynamic stresses. If static stresses fall within design limits and the measured low-cycle fatigue stresses allow components to meet the required design life, the engine meets the success criteria for this testing.

Sea-level development testing is conducted early in the development test plan. The engine is tested in a sea-level test cell (i.e., sea-level pressures, temperatures, and operating conditions). Sea-level testing begins at ambient inlet pressure and temperature and later includes elevated inlet pressure and temperature conditions to simulate effects due to the Mach number. Sea-level development testing is used to evaluate engine steady-state performance (thrust, SFC), transient performance (starting, accelerating and decelerating, augmentor lighting, and shutdown), individual component efficiencies and stresses, control systems functions, lubrication system functions, cooling flows, durability, and operability. These assessments are made using static and dynamic strain gauge measurements of flowpath pressures, temperatures, airflow, rotor speeds, fuel flow, thrust, lube-system pressures and temperatures, and control-system signals. The intent of this testing is to evaluate all engine characteristics and functions and to address any deficiencies prior to proceeding to altitude testing.

Altitude testing essentially repeats sea-level testing conducted at key flight conditions and is used to verify flight worthiness prior to entering flight test. It is conducted in an altitude chamber that is specially equipped to simulate operating conditions throughout the flight envelope. Engine inlet pressure and temperature are set to be consistent with the altitude and speed conditions to be simulated. At the same time, ambient pressure in the test chamber is made to be consistent with the altitude being simulated. Altitude testing is used to evaluate steady-state and transient engine performance, component efficiencies and stresses, control system functions, operability with distortion, augmentor operability, combustor operability,[10] thrust, cooling flow, lubrication system function, vibration, and windmilling capability. Instrumentation and data collection are very similar to those used in sea-level testing. The intent of altitude testing is to evaluate engine characteristics and functions throughout the flight envelope and address any deficiencies prior to flight test in an effort to reduce overall program risk.

Three to four test engines within the development program would typically be designated for endurance testing and accelerated mission testing (AMT), hot section life verification, and formal qualification. Endurance testing is conducted in a sea-level test cell and is used to verify that the life of critical hot and cold section engine parts meets design and specification requirements. Engine endurance is now demonstrated using an AMT. The AMT uses a mission-based simulation, called a *duty cycle,* to subject the engine in the test cell to the conditions it is likely to experience in actual operation. In

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[10] More specifically, the ability of the combuster and the augmentor to light and their blowout and auto-relight characteristics are tested throughout the simulated envelope.

constructing the duty cycle, the engine designer studies the system's full spectrum of projected mission profiles. The designer then develops a "composite" cycle that reflects, in a compressed period of testing, a series of representative throttle settings, transients, dwell times, pressures, and temperatures. So, for example, one hour of endurance testing is designed to duplicate the structural demands of multiple hours of mission operation in the aircraft. Cycles are now run on an automated schedule in the test cell to allow for rapid accumulation of endurance hours in a minimal number of test hours. This reduces test costs and allows endurance testing to stay ahead of the fleet when introducing new components. Successful completion of this durability testing and certification means that no additional development effort is required for full specification compliance and leads to approval of the OCR milestone. The OCR milestone demonstrates system durability, which was not addressed by the MQT, and was added to provide a more reliable fielded system to the operator.

Hot and cold section life verification is one of the elements of endurance testing. A tailored duty cycle may be developed to target damage accumulation specifically at hot or cold section parts because the life of these components is typically affected by different types of operation. A series of these types of tests is run throughout the development program.

Often, the program will designate a test engine for the sole purpose of milestone qualification. This dedicated qualification vehicle is used to verify that the engine's final configuration, with all design modifications incorporated, meets all specification requirements. Qualification testing usually includes a repeat of much of the engine testing done in the development program on this single, final configuration engine. In some cases, where time or funding is constrained, data from earlier development testing may be accepted for official qualification if significant modifications have not been made to the engine configuration.

Controls and integration testing verifies the functionality and compatibility of engine systems and aircraft systems that must interface. Integration begins at the component level, continues during engine testing in the sea-level and altitude test cells, and follows into flight test. This testing includes evaluation of the engine control system as it interfaces with the aircraft mission computer and cockpit displays, electrical system, inlet, airflow bleed, horsepower extraction, fuel systems, mechanical interfaces, and engine bay cooling. Given that today's aircraft are migrating toward fully integrated propulsion and flight controls, this testing becomes an even more critical component of the development program, and it is likely that the demands in this area of the development program will continue to increase.

Environmental testing verifies satisfactory engine operation, performance, and durability when the engine is subjected to extreme conditions that are anticipated in service. This testing can include, but is not limited to, bird, sand, or water ingestion, steam ingestion, operation with water-saturated fuel, anti-icing capability, corrosion testing, and the like. The specifics and extent of environmental testing that is conducted are based on the requirements of individual programs.

Once the cadre of test assets is established, the timing and sequencing of this test work become as critically important as the actual tests that are conducted. Individual engines are not run continuously through the development program (although there are always engines in the test cycle). Instead, engines are run in specific blocks of time, depending on the type of test to be run and the data to be collected. The down time between engine runs is used for data analysis, hardware inspection, design changes, hardware rebuild, engine reconfiguration, and transportation. Information gathered from the testing, monitoring, and inspection of one engine is transferred into subsequent builds to ensure that the most timely and representative hardware and software configurations are rigorously tested. Engine development testing takes a building-block approach, with confidence in the system's ultimate performance gradually building and working up to qualification of full system capability.

The notional test plan in Figure C.2 shows FETT 18 months after System Development and Demonstration contract authorization. This assumes a significant amount of component rig and core engine work has been completed in the Concept and Technology Development and enough funding is in place to provide for long-lead-time material and hardware fabrication. After the first full engine goes to test, more engines are added to the test program based on the contractor's ability to provide those additional engines and the availability of adequate funding. By the PFR milestone, a good portion of the sea-level and altitude development, operability, and functionality test work, and some AMT/endurance testing, should be complete. By the low-rate production milestone, all functional and performance requirements should be verified. All sea-level and altitude development and altitude performance work should be complete. By the high-rate production milestone, hot section life verification and all AMT/endurance testing should be complete, and the system should have demonstrated full compliance with the specification requirements.

Adequate funding, and the appropriate funding stream, is critical in successfully completing the objectives of the development program. Because the start of an engine development program is hardware-intensive, most recent programs have required a financially front-loaded funding profile. The profile levels out in the middle of the program to support sustained testing and increases toward the end of the System Development and Demonstration portion of the program to provide for final qualification and flight test support.

Because of the critical interaction among weapon-system and engine-level milestones, schedules, required assets, test sequencing, and the associated costs and funding profiles, the formulation of aircraft and engine development plans has evolved into a cooperative process to ensure the successful achievement of program milestones at all system levels.

TRENDS IN MILITARY ENGINE DEVELOPMENT

Intuition might suggest that as technology improves and design, testing, and evaluation tools become more sophisticated, development time and cost for new systems should decrease. However, this is not the case, and customers are demanding increasingly greater performance, durability, and affordability from their systems.

Much of the performance advantage in turbofan engines has been achieved through the use of lighter-weight, exotic materials and significantly more-complex geometry. Any cost or schedule advantage associated with the application of advanced technologies or design tools is quickly offset by the design complexity required to meet these increased system demands. In addition, in many instances, even though tools with greater capability are available, their use is curtailed by limited computing capacity or delayed due to the effort (and funding) required to develop them fully for use in a specific application.

When more-capable tools are fully applied, they allow an engineer to perform many design iterations to reach the "optimal" solution. However, this solution is not produced with a reduced number of engineering hours, but it does come during the development stage rather than post development. Thus, advanced modeling and simulation tools allow designers to identify and correct technical problems early, thereby avoiding some potentially costly hardware failures either during the test program or in the field. In addition, better predictive tools provide more accurate forecasts of future operational performance. These improved predictions should allow for more accurate maintenance planning and cost savings in the operation and support phase of the engine life cycle. Development costs are not likely to decrease due to advanced tools and technologies. Rather, the payoff is in systems that are significantly more capable and more reliable with comparable development costs and a comparable development schedule.

System performance requirements will continue to escalate as military requirements become more demanding and new or emerging technologies becomes available. The U.S. armed forces will always demand that their weapon systems continue to outperform the systems of their adversaries, both tactically and logistically. Turbofan engine technology faces numerous challenges that may alter how development programs are conducted in the future. For example, increased stealth/LO requirements imposed on an engine/propulsion system could result in the use of more-exotic materials and coatings and more-complex inlet and exhaust designs. More-stringent noise and emissions standards will impact the complexity of the design and could require additional design and test time. The integration of flight and propulsion controls also could dictate system complexity and require additional design and test time. The prudent development and application of advanced technology will play a critical role in meeting these challenges and affordably maintaining the U.S. military's tactical advantage.

Appendix D

MODERN TACTICAL JET ENGINES

Ever since the Wright brothers redesigned their piston engine to reach a usable power-to-weight ratio for their Wright Flyer, aircraft propulsion systems have been a critical element in aircraft design and performance. U.S. military and civilian customers have placed high priorities on flight safety, engine performance, reliability, and life-cycle costs. The design and maintenance of safe, affordable, and reliable high-performance engines require the integration of many technical disciplines including aerodynamics, thermodynamics, fluid mechanics, solid mechanics, materials, fuels, combustion, heat transfer, and controls. The resulting jet engines are complex devices, which stress the limits of U.S. capabilities in each of these technical disciplines.

Pushing the state-of-the-art in integrated technologies leads to discoveries of new technical challenges both within these technological areas and at the points these technologies intersect. Because the application of new or refined jet engine technologies has been fairly continuous, so has the flow of new technical and support challenges. This situation is compounded for front-line fighter engines by the expansion of the flight envelopes for successive fighters. As we discussed in Appendix A, engine manufacturers, in cooperation with their customers, conduct rigorous development and testing programs, including AMT, to solve as many technical problems as possible before the engines are fielded. However, some problems are not manifested until the engine is stressed in actual combat or rigorous training environments, and sometimes not until engines have been operated for thousands of hours.

Technological advances are normally incorporated in one of three ways: new technologies are integrated into existing engine designs through component modifications[1] to correct specific problems, numerous technologies are integrated into a mature engine to create a derivative engine design, or an entirely new engine is developed. The extent of redesign to develop derivative engines varies. For example, the F110-PW-129 has approximately 80 percent parts commonality with its predecessor, the F110-PW-100, while the F100-PW-229 has approximately 20 percent to 30 percent parts commonality with the F100-PW-200 (Kandebo, 1998c, p. 22). In most cases, derivatives of existing engines typically introduce fewer unforeseen technical challenges than entirely new engines.

We next briefly describe several tactical aircraft engines that either are currently in the Air Force's inventory or could be in the near future. Not included are engines for transport and training aircraft, expendable missiles, unmanned aerial vehicles, and auxiliary power units (APUs).[2] These other engines and APUs will also continue to integrate new technologies, with emphasis on the performance, reliability, and affordability factors that are most important to their applications. The Air Force's *Engine Handbook* (1998) contains summary specifications for a large variety of Air Force engines.

EXISTING AIR FORCE TACTICAL AIRCRAFT ENGINES

F100-PW-220

This P&W engine is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-15 and F-16 aircraft, having passed military qualification testing in 1985. Under takeoff conditions, this engine can produce 23,770 pounds of thrust with the afterburner lit ("wet") and 14,590 pounds of thrust with the afterburner turned off ("dry") (*The Engine Handbook*, 1998, p. 24).

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[1] The Department of Defense conducts component modification through what it calls the Component Improvement Program.

[2] APUs are essentially small turboshaft engines, which are used to provide electrical power or pressurized air. They are either mounted in ground-power carts or are integrated into some aircraft.

F100-PW-229

This is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-15E and F-16C/D aircraft. This growth derivative of the F100-PW-220 was qualified in 1989. Under takeoff conditions this engine can produce 28,500 pounds of thrust wet and 17,000 pounds dry (*The Engine Handbook,* 1998, p. 25).

F100-PW-232

This is a growth version of the F100-PW-229. The F100-PW-232 is not currently in the Air Force inventory but could be used in U.S. Air Force or foreign F-15E and F-16C/D aircraft. Existing F100-PW-229 engines can be modified to this configuration by using kits that are available from Pratt & Whitney.

The primary enhancement over the F100-PW-229 is a redesigned fan. This fan provides up to 10 percent higher airflow through improved aerodynamics, and does so at a higher efficiency (Kandebo, 1996a and 1998b). This new fan can increase the thrust of the engine or can extend the engine's hot section design inspection interval from 4,300 total accumulated cycles (TACs) to 6,000 TACs by lowering the maximum turbine inlet temperature by approximately 120°F while maintaining the F100-PW-229's maximum thrust level. In addition, the second and third stages of the new fan are integrally bladed, meaning that each stage's rotating blades and rotor (disk) are a single piece. These one-piece bladed disks (blisks) reduce the engine's part count, reduce weight and aerodynamic losses, and eliminate each rotor blade's traditional dovetail attachment roots, thereby precluding the common problem of cracks forming in the blade's root. The fan's first-stage blades are attached to their disk in a conventional manner "to allow easy field replacement" of blades due to FOD or bird strike (Colaguori, 1998). In addition, the fan's rotor blades have lower aspect ratios (the blades' radial length divided by axial length) than the corresponding F110-PW-229 fan blades, making them sturdier and, therefore, less susceptible to damage from bird strike or FOD.

F110-GE-100

This GE engine is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-16 aircraft and was qualified as a military engine in 1985. Under takeoff conditions, this engine can produce 28,620 pounds of thrust wet and 18,330 pounds of thrust dry (*The Engine Handbook,* 1998, p. 32).

F110-GE-129

This is a low-bypass-ratio, mixed-flow, afterburning turbofan used to power Air Force F-16C/D aircraft and has also been qualified for the F-15E (Kandebo, 1998b). This growth derivative of the F110-GE-100 was qualified in 1989. Under takeoff conditions, this engine can produce 28,737 pounds of thrust wet and 17,155 pounds of thrust dry (*The Engine Handbook,* 1998, p. 33).

F110-GE-132

Also known as the F110-GE-129 Enhanced Fighter Engine, this growth version of the F110-GE-129 is not currently in the Air Force inventory but could be used in U.S. Air Force or foreign F-15E and F-16C/D aircraft. Existing F110-GE-129 engines can be modified to this configuration using kits available from GE. As in the corresponding P&W engine (F100-PW-232), GE's F110–GE-132 has a more efficient and higher airflow fan with lower-aspect-ratio blades. As in the F110-PW-232, the F110-132's improved fan can be used to increase the thrust of the engine or to extend the hot section design inspection interval to 6,000 TACs. All three rotors in this fan are blisks. In addition, the F110-GE-132 has a redesigned afterburner, which incorporates technologies developed by GE for the F414-GE-400 afterburner. This enhanced afterburner is less complex and produces more thrust than its predecessor, and should also be more reliable (Kandebo, 1996a and 1998b).

Under an Air Force contract, GE has also developed an ejector nozzle, which has 400 fewer parts than current F110 nozzles. In addition to its normal thrust-producing function, this nozzle draws cool air from the engine bay and across the nozzle flaps and seals to keep the nozzle cooler. GE predicts this cooling effect will quadruple the nozzle's life and will reduce its infrared signature. This advanced nozzle can be used on most F110 engines, just not the F110-GE-132 (Jane's Information Group, 1999b).

F404-GE-F1D2

This GE engine is a nonafterburning, low-bypass-ratio, mixed-flow turbofan used in the subsonic F-117 stealth aircraft. It is derived from the family of afterburning and nonafterburning F404s, which the U.S. Navy and other services operate in F-18A/B/C/D and other aircraft. Under takeoff conditions, the F404-GE-F1D2 produces 10,000 pounds of thrust ("F-117 Engine Design ...," 1990, p. 27).

TF34-GE-100

This GE engine is a high-bypass-ratio turbofan engine used in the subsonic A-10 attack aircraft. It was first used in the Navy's S-3A antisubmarine aircraft. The civilian variant, CF34, has been very successfully grown to increased thrust levels and employed on regional jets. Under takeoff conditions, the TF34-GE-100 can produce 10,540 pounds of thrust (*The Engine Handbook,* 1998, p. 39).

FUTURE ENGINES FOR AIR FORCE TACTICAL AIRCRAFT

F119-PW-100

This is a low-bypass-ratio, mixed-flow afterburning turbofan being developed for the Air Force's new F-22 fighter. The engine will enable the F-22 to supercruise (cruise supersonically without afterburning). The F119's component designs push the state-of-the-art to give it exceptional performance; it should also provide exceptional reliability. In fact, P&W's YF119 was chosen for the F-22 over GE's YF120, primarily due to the lower development risk, production cost, and expected maintenance requirements (Bond, 1991).

The F119 is equipped with a 2-D thrust-vectoring nozzle to enhance the F-22's maneuverability. The engine's full authority digital engine control is integrated with the aircraft's flight control system. Further, this will be the first operational engine in which the low- and high-pressure spools rotate in opposite directions. (A *spool* is essentially a compressor and the turbine that drives it, along with the shaft that connects the two rotating components.) All compressor and fan stages are integrally bladed. The fan's first-stage blades are also hollow to save weight and enable the engine to respond more rapidly to throttle changes. The F119's floatwall combustor design should reduce the problems that are typically associated with thermal stresses in combustor liners (Jane's Information Group, 1999c).

Engine maintenance improvements have been designed into the F119 based on lessons learned from previous engines. For example, almost none of the line replaceable units that are external to the engine are stacked on top of one another, fasteners are standardized, and key portions of the external plumbing are flexible hosing. The engine's main case is split at the fan and at the compressor to permit rapid access to those components. Overall, the engine has 40 percent fewer parts than the F100 ("P&W to Test …," 1994). P&W has predicted that engine deployments will require 75 percent less airlift and will require 220 pieces of relatively compact ground support equipment, compared with the 400 pieces required by the F100-PW-229. F119 maintenance personnel will use electronic tech manuals, replacing approximately 85,000 pieces of paper that would have been required with traditional manuals. In addition, electronic updating of these manuals will save extensive flightline maintenance manpower, compared with traditional methods (Kandebo, 1995b). Using the F100-PW-220 as a baseline, P&W expects shop visit rates to be reduced 74 percent, unscheduled engine removal rates to be reduced 33 percent, and maintenance man hours per flight hour to be reduced 63 percent ("F119 Configuration …," 1991).

F135

The P&W F119 was also chosen as the engine to power the JSF demonstrators in the concept development phase. However, the F135, a derivative of the F119-PW-100, is being developed to meet the JSF requirements. Rear Admiral Craig Steidle, former U.S. Navy JSF program director, stated that the propulsion system is the greatest technical challenge for the JSF (Warwick, 1997).

For all the JSF variants, maximum thrust will increase from 35,000 pounds to approximately 40,000 pounds. The primary technology enhancements that enable the F135's increased airflow and higher RIT will be the incorporation of P&W's "superblade" cooling in the high-pressure turbine, gamma titanium aluminide blades in the last compressor stage, an enhanced cooling airflow pattern in the combustor, and high-temperature fuel nozzles to prevent coking (Kandebo, 1998a and 1998d). As in the case of the F-22, the JSF will have integrated flight and propulsion controls. To test and refine these highly integrated control systems, the manufacturer's engineers will run their aircraft simulators with the engine control systems integrated and controlling engines running on thrust stands.

All variants will also have electronic prognostics, which may include the capability to inform maintenance personnel of repair requirements before a component fails and before the JSF lands (Smith, 1999, and Kandebo, 1998d). Norris (1999) reports that the prognostic and diagnostic systems being developed and considered for the JSF include acoustic, electrostatic, and eddy current monitoring. If fielded, these systems will be capable of detecting and discriminating between types of FOD entering the inlet, "hearing" changes in bearing noises, and sensing when the exhaust stream contains unusually high levels of charged particles. High levels of charged particles in the exhaust stream are characteristic of a damaged engine or one undergoing abnormal wear (Norris, 1999, and Nordwall, 1992).

As of 1998, P&W was predicting that F119-JSF deployments would require 60 percent fewer C-141 loads per fighter wing, support costs would be 60 percent lower, and the mean time between maintenance would be twice that of today's engines. In addition, the Conventional Takeoff and Landing versions of the JSF would have 50 percent fewer in-flight shutdowns than the F100-PW-220, and the STOVL version would have 80 percent fewer in-flight shutdowns than the AV-8B's "Pegasus" engine (Kandebo, 1998d).

Boeing's X-32 used a thrust-vectoring 2-D nozzle. It also incorporated a second stage in the F119's low-pressure turbine to help drive a fan that flowed 10 percent more air than the F119-PW-100. The STOVL variant diverted the engine's exhaust through rotating and retractable lift nozzles located near the center of the aircraft and some fan air through a "jet screen" nozzle located a few feet in front of the lift nozzles (Jane's Information Group, 1999c). The resulting jet screen was a barrier of cool clean air from the engine's fan, which provided some lift and prevented the engine exhaust from recirculating into the engine inlet. Minority partner Rolls-Royce developed the lift nozzles and jet screen hardware. Small pitch, roll-and-yaw nozzles were integrated near the engine's main nozzle to provide stability control during STOVL operations. The engine was also stretched several feet by inserting an extra duct (essentially a large tube) upstream of the afterburner in order to move the main engine forward, enabling placement of the vertical lift nozzles in the appropriate location with respect to the aircraft center of gravity.

Lockheed-Martin's X-35 (the winner of the competition) used a low-observable axi-symmetric nozzle. Its STOVL variant used a shaft driven vertical-lift fan just behind the cockpit, roll control ducts in the wings, and a large three-bearing swivel duct to rotate the main nozzle to point vertically downward during STOVL operation. The lift fan's shaft was driven by the F119's low-pressure spool and connected by a clutch and gearbox. Minority partner Rolls-Royce developed the three-bearing swivel duct and roll control duct. Similarly, Allison, a division of Rolls-Royce, developed the lift fan hardware (Kandebo, 1998d, and Warwick, 1997).

F120

The Air Force and GE have continued to mature and enhance the F120 through the IHPTET program since the Advanced Tactical Fighter program source selection in 1991. This has reduced the risk and uncertainty of this variable-cycle afterburning turbofan. Due to the large number of JSFs to be built and the desire to use competition to keep prices low and performance and reliability high, the JSF program has selected the F120 to be the "alternate engine" for the JSF. If this program follows the precedent set by the F-16, the Air Force will have JSFs fielded with both derivatives of F119 and F120 engines starting after 2010. The JSF version of this engine will be developed and built by a team led by GE, with Rolls-Royce participating.

The F120's variable-cycle capability allows the engine to change its bypass ratio as appropriate over the aircraft's flight envelope. This functionality requires additional control logic and flow control hardware. Other advanced technologies in the F120 include combustor and high-pressure turbine blades and vanes made of Rolls-Royce's (Allison's) "Lamilloy." Lamilloy is essentially a material made of laminated layers of high-temperature perforated metal materials. Compressor bleed air is blown into and through the Lamilloy components to effect transpiration-like cooling of those components. Also included are counter-rotating high- and low-pressure spools, without the traditional stationary turbine vanes between the turbine rotors. The shafts will turn on bidirectional tapered roller bearings. The F120 will have an advanced afterburner, based on technologies from GE's F414 engine, used in the F/A-18 E/F (Kandebo, 1997). The nozzle will be an advanced low-observable axi-symmetric nozzle, which GE states will have half of the weight and 40 percent of the cost of a 2-D nozzle (Kandebo, 1996a).

SUMMARY

The United States continues to lead the world in fielding state-of-the-art jet engines. The implications of integrating new technologies into military aircraft engines are both positive and negative. The Department of Defense and industry are making a concerted effort to enhance affordability, extend component life, increase reliability, automate prognostics and diagnostics, simplify maintenance procedures, and enhance performance. However, the continuous integration of new technologies into existing and new engines, and expanding flight envelopes, will likely continue to create a corresponding flow of technical challenges and costs. We hope the brief descriptions we supplied in this report of some current and future U.S. tactical aircraft jet engines will assist military weapons system program office personnel in understanding military jet engines and estimating their life-cycle costs.

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