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