COMMERCIALIZATION AND TRANSFER OF TECHNOLOGY IN THE U.S. JET AIRCRAFT ENGINE INDUSTRY

by

Jerry R. Sheehan

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Signature of Author ______________________________
Department of Aeronautics & Astronautics
May 10,1991

Certified by: ______________________________
Theodore A. Postol
Professor of Science, Technology, and National Security
Thesis Supervisor

Certified by: ______________________________
Professor Richard de Neufville
Chair, Technology and Policy Program

Accepted by: ______________________________
Professor Harold Y. Wachman
Chairman, Department Graduate Committee

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ABSTRACT

This thesis examines the changing nature of technology transfer between military and commercial research and development programs in the U.S. jet aircraft engine industry. Early technology transfer in the jet engine industry is shown to have been characterized by the direct commercialization of military engines. Future technology transfer is projected to consist of the transfer of basic research results from military to commercial programs. As a result, it is argued, the military can be expected to assume less of the cost and risk associated with the development of future commercial engines than it formerly did.

Prospects for future technology transfer are evaluated by determining the types of engines likely to be developed for military and commercial aircraft. The effects of increased specific thrust and improved fuel economy upon aircraft range, speed, and fuel consumption are demonstrated by analyzing the aerodynamic performance of military fighter, bombers, and transports and of commercial airliners. The technologies necessary to meet the requirements of future military and commercial engines are explored through ideal cycle analysis. As is shown, military and commercial engines can both benefit from additional research in the areas of advanced materials, compressor design, and component efficiencies. However, advances in commercial engine design will also require additional research in areas such as advanced nacelle design and fan blade aerodynamics.

This analysis indicates that future technology transfer between the military and commercial sectors of the engine industry will be characterized more by the transfer of basic research results than by the direct commercialization of military hardware. The implications of this change upon the development of policies for maintaining the competitiveness of the U.S. jet aircraft engine industry are presented and discussed.

Thesis Supervisor: Dr. Theodore A. Postol
Professor of Science, Technology, and National Security

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CHAPTER I

INTRODUCTION

Over the past several decades, the U.S. aircraft industry has maintained a highly competitive status in both the domestic and international markets for military and commercial aircraft. In constant dollars, domestic sales of U.S. aircraft, engines, and parts have increased over fifty percent since 1975, and despite the growing trade deficit for U.S. general merchandise, the trade balance for the American aerospace industry has continued to grow, from approximately $1.5 billion in 1964 to over $22 billion in 1989 (AIAA, 1991, p. 121). The reasons for such success are many and include economic, political, technological, and personal factors. In addition, it is also clear that the role of the U.S. government--and the U.S. military in particular--in creating and supporting the aircraft industry cannot be overlooked.

A. Military-Commercial Relationships:

The large military buildup during the Second World War created a vast infrastructure in the U.S. and abroad for the design, fabrication, and production of military aircraft. U.S. manufacturers were able to take advantage of the infrastructure the government had helped construct and developed it into successful military and commercial aircraft industries (NAS/NRC, 1985, pp. 26-27). The European nations that until then had lead the U.S. in aviation, however, were unable to properly mobilize their manufacturing bases after the war. Much of Germany's industrial infrastructure was destroyed by the war; what remained was prohibited from being used for the production of aircraft for more than a decade after the war. Great Britain's aircraft industry remained fragmented among a number of different manufacturers who failed to consolidate into a unified industry with the capacity and financing to launch a major research and development effort. France's aircraft industry focused solely upon national air transportation and hence had little motivation to develop long-range aircraft (MIT, 1989, p. 21).

The U.S. was well-situated to take advantage of its aircraft industry after the war. Government investments had developed a strong industrial base from which the industry could grow, and the military continued to invest in advanced aircraft technology. By emphasizing the role of the Air Force in its defense policy, the U.S. government generated an expanding market for military aircraft and provided aircraft manufacturers with an assured market for their products.

The commercial aircraft manufacturing industry took advantage of such government spending through the successful transfer of military technology to commercial applications. In general, this process can take two forms that will be referred to throughout this study as "commercialization" and "technology transfer". Commercialization refers to the direct development of a commercial product from military hardware. In the aerospace industry, commercialization can result from the conversion of a military transport into a commercial airliner or the use of a military engine on a commercial aircraft with minor modification. The term "technology transfer", as will be used in this context is more encompassing. It can refer to either commercialization or to the transfer of technical know-how between two industrial sectors. Thus, a piece of hardware need not be transferred directly between sectors, rather the process for developing the technology can be transferred and then used for a new application. Examples of such transfer include new materials and processing techniques that can be used to develop components for different military and commercial engines.

The commercial aircraft industry has benefitted from military research and development (R&D) in both these ways. In developing the 707 airliner, for example, Boeing developed a prototype transport[1] aircraft that they knew could be converted into a commercial airliner. At the same time, their design for the prototype represented an outgrowth of the company's work on the B-47 and B-52 bombers. The design of the 747 made use of the knowledge Boeing gained in bidding for the Air Force's C-5 heavy transport aircraft. Similarly, until the early 1980s, virtually all commercial jet engines in operation on major passenger transports were derived from military antecedents. General Electric's CF6 series engines which now power the Boeing 747 and 767, the McDonnell-Douglas DC-10, and the Airbus 300, 310, and 330 aircraft derive with only minor modification from the TF-39 engine originally designed and constructed to power the C-5. Pratt & Whitney's JT9-D engine which powers versions of the Boeing 747 and 767 and Airbus 300 and 310 aircraft also derives from the engine that Pratt had proposed for the C-5 competition.

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[1]The prototype aircraft was designated the 367-80. It served as the prototype for both the 707 and the KC-135 military transport.

B. A Changing Environment in the Aerospace Industry:

The aircraft industry is at present undergoing a period of change which threatens to alter the relationship between the commercial and military markets and the nature of the industry itself. This change reflects both the evolution of domestic policy and developments on an international level. Three primary trends characterize this change: an increasing divergence between military and commercial requirements for aircraft and their engines; a declining military budget; and changes in the nature of competition in the commercial aerospace and airline industries.

1. Diverging Military and Commercial Requirements:

A number of reports suggest that future military R&D in jet aircraft engines will provide limited benefit to the commercial market because the requirements of the two sectors are rapidly diverging (MIT, 1989; NAS/NRC, 1985). In other words, the two sectors of the market may now be developing engines that have little hardware in common. The divergence limits the amount of military technology that may be validated for commercial use. As the MIT Commission on Industrial Productivity concluded in its study of the U.S. aircraft industry:

> The commercial sector is now enjoying less spin-off from military validation of new concepts....While divergence between military and commercial needs is greatest at the product level, differential mission requirements appear to be reducing the amount of generic technology validation useful to commercial producers. In combination with fewer military programs overall, the military is fulfilling this important function to a much smaller extent than it formerly did (MIT, 1989, p. 17).

The growing divergence between military and commercial engines derives primarily from changing design constraints in each sector. Throughout the 1950s and 1960s, military transports and bombers were designed for maximum payload and maximum range as were commercial airliners. Hence, the engines developed by the military had exceptional utility in commercial applications; both required high thrust and moderate fuel economy. However, recent military engine development has not continued along these lines. The military is only now developing its first large transport in over twenty years and so has not been funding development of large transport engines. In fact, the military plans to use a modified commercial engine on its new C-17 transport aircraft. Furthermore, engines developed for modern bombers such as the B-1A and B-2 have been designed with requirements for supersonic capability and stealth as primary design constraints. Thus, they tend to trade off fuel efficiency for size so that they may be easily incorporated into airframes.

As a result, recent military engine development has focused on fighter-sized engines which have then been modified for use on bombers. These engines must produce sufficient thrust to accelerate jet aircraft to high subsonic or supersonic velocities. At the same time, they must meet stringent size and weight restrictions in order to be easily integrated into small, lightweight airframes that have low aerodynamic drag and present low radar cross sections. Thus, these engines usually take the form of low bypass ratio turbofan engines (sometimes referred to as "leaky turbofans"). In these engines, most of air ingested at the engine inlet passes through the engine core and is combusted; only a small fraction of the air "bypasses" the core and is later mixed with the core flow. These engines provide improved thrust-to-weight ratios compared to higher bypass ratio engines, but at the expense of fuel efficiency.

In contrast, the commercial sector is more concerned with operating costs. It measures engine performance primarily in terms of specific fuel consumption (SFC), the number of pounds of fuel that must be burned each hour to produce one pound of thrust. Lowering the SFC of an engine decreases the amount of fuel the aircraft will use during a flight and thus reduces the direct operating cost (DOC) of the airliner.

Since the mid-1960s, commercial airlines have attempted to lower SFC by using large, high bypass ratio turbofan engines in which a large quantity of air is channeled around the engine core. Because of the large masses of air these engines handle, they tend to be both heavy and large and therefore are not suitable for most military fighter or bomber aircraft. On commercial aircraft, these drawbacks are outweighed by gains in SFC which lower airliner operating costs so that airlines can be yet more competitive.

Design constraints for military and commercial engines therefore appear to be diverging. Whereas the engines developed for military transports and bombers in the 1960s had direct commercial application in many instances, the engines developed for modern military aircraft do not. As a result, the aircraft engine industry is developing different types of engines for each sector and the amount of directly commercialized military hardware is declining.

2. Declining Military Budget:

In addition, government expenditures on military R&D are expected to decrease over the next decade due in large part to the declining Soviet threat. Current projections estimate that the defense budget for R&D will decrease 1% in real terms in Fiscal Year (FY) 1993, 6% in FY 1994, 10% in FY 1995, and 7% in FY 1996 (Gilmartin, 1991, p. 51). While the recent Gulf War may temper these cuts somewhat and sustain funding for certain areas of research and development such as smart munitions and stealth aircraft (Shifrin, 1991, p. 62), the overall trend will be toward a reduced military budget for R&D.

Military budget cuts could adversely affect the aircraft engine industry. Reductions in funding for advanced engine research may decrease the amount of new gas turbine technology developed with government funding. Despite the fact that much military engine hardware cannot be directly commercialized, much of the basic technology developed for military engines such as efficient compressors and high-temperature ceramic materials still has commercial application. The commercial industry continues to benefit from the transfer of this technology from the military sector. Without this source of technology development, the commercial industry may be forced to fund this research itself.

Reductions in military procurement may also effect the size of the industry and hence its ability to conduct large scale R&D programs. Reductions in the number of B-2 bombers to be produced and cancellation of the Navy's A-12 stealth attack aircraft have placed airframe manufacturers in a precarious position. Analysts estimate that excess capacity caused by these and other cutbacks will force up to three of the six current airframe manufacturers to withdraw from the industry (Velocci, 1991, p. 63). Cancellation of aircraft programs also hurts the aircraft engine manufacturers as they must produce fewer engines. The cancellation of the A-12, for instance is likely to cost General Electric as much as 2.5 billion dollars in lost sales of the F412 engine and an equal amount in lost sales of spare parts. In the near term, the cancellation may affect "at least several hundred employees" who had been working on F412 engine development (Aviation Week, 1991a, p. 19).

Combined with the already limited number of new military starts, military budget reductions would place an additional financial burden on the aircraft industry. Commercial sales would have to increase in order to sustain the size of the industry and to produce sufficient profit to fund basic research and development. In an industry in which military work provides a disproportionate amount of corporate profit and commercial profit margins are low, such a change may be difficult to survive.

3. Changes in the Basis of Competition:

The early success of the U.S. aircraft industry was influenced by domestic policies that encouraged technological innovation. The establishment of the Civil Aeronautics Board (CAB) in 1938 to control entry into the airline industry and regulate pricing and route structures stimulated "service-based competition" (MIT, 1989, p. 22) throughout the industry. Because the CAB established airline fares along different routes, competitors could not compete on a price basis, and airlines were encouraged to adopt new technologies for their fleets such as new aircraft and engines in order to attract additional passengers.

Deregulation of the airline industry in 1978 has shifted the basis of competition from service to price. Without CAB regulated fares, airlines can no longer afford to purchase new technologies unless they can be shown to reduce direct operating costs and hence be used to enhance profitability. In many cases, the price airlines are now willing to pay for new technology does not cover the cost of developing and producing these technologies (MIT, 1989, p. 31).

At the same time, competition from foreign manufacturers has become more intense. After a period of financial difficulties which led to public ownership, Rolls-Royce has reemerged as a viable competitor in the aircraft engine business. Despite lagging GE and Pratt in thrust-to-weight ratio and turbine inlet temperature during the 1970s, Rolls-Royce has since gained parity (or near-parity) with the U.S. manufacturers in these areas (NAS/NRC, 1985, p. 123). Airbus Industries, a consortium of European airframe manufacturers, has also proven a viable competitor in the aircraft industry with its A300 series of wide-body airliners.

Many of these foreign competitors such as Airbus and SNECMA, a French engine company, receive support from their national governments in the form of government subsidies and low-interest loans. This support has undoubtedly contributed to their recent success. U.S. aircraft and engine manufacturers do not receive such subsidies, but many analysts argue that U.S. military procurement provides similar support (Markillie, 1988, p. 5; MIT, 1989, p. 18). As requirements for military and commercial aircraft and engines continue to diverge, however, the degree to which such indirect support will continue is questionable. Such a trend may therefore adversely affect the ability of the commercial aircraft industry to compete with international competitors that benefit from direct government support.

Together, the three trends identified above imply that the nature of the aircraft industry may undergo revolutionary changes. As such, they dictate a need to reexamine the U.S. aircraft industry in the light of the changing environment in order to develop a coherent strategy for anticipating and responding to these changes. An examination of this sort will have to address a wide range of topics including the reasons for the past success of the U.S. industry, the nature of business-government relations, and the shape of the future aircraft and airline industries.

C. Objective of This Thesis:

This thesis begins such a reexamination by investigating the relationship between military and commercial jet engine technology. In particular, it evaluates the effectiveness of military funding in supporting research and development applicable to the commercial jet aircraft engine industry. As such, this thesis represents a case study applicable to the larger questions of technology transfer between military and commercial industries and the future of the U.S. aerospace industry in general.

This thesis is proactive in that it attempts to determine, from a technical perspective, the extent to which the changing relationship between military and commercial jet engine technology may affect the future competitiveness of the jet engine industry as a whole. While the industry appears to have successfully accommodated past changes in this relationship, its success in handling future changes may rest on its ability to predict the effect of such changes and to adapt to them knowledgeably. The analysis contained in this thesis is geared toward identifying areas in which military and commercial engines will continue to diverge and toward providing leadership to policy-makers and business planners so that they may properly respond to the potentially new environment ahead.

The jet engine industry is particularly interesting in the context of technology transfer for a number of reasons. First, jet engine technology is an enabling technology for the aircraft industry as a whole. Advances in jet engines pace advances in aircraft capabilities. Neither supersonic flight nor profitable intercontinental flight would have been possible without the advances in jet engine technology. Thus, the future of aviation may best be determined from a study of the propulsion industry.

Secondly, the aircraft engine industry is dominated by a limited number of engine manufacturers. Whereas nine U.S. companies manufacture gas turbine engines[2] for commercial and military applications, two of these companies, General Electric (GE) and Pratt & Whitney (Pratt), dominate both the commercial and military markets. In fact, GE and Pratt are the only U.S. engine manufacturers that produce engines for large commercial transports that carry over 90 passengers such as the Boeing 700 series aircraft, the McDonnell-Douglas DC-8, DC-9, and DC-10 aircraft, and the Airbus 300 series. They are also the sole U.S. suppliers of military engines for fighter and bomber aircraft. Thus, these two companies are in a particularly promising position to benefit from the transfer of technology between military and commercial programs. As suppliers to both sectors of the market, Pratt and GE are well positioned to transfer military technology into commercial products.

D. Structure of Thesis

This thesis is divided into six chapters which attempt to lead the reader to a number of conclusions regarding the role of military research upon the commercial jet engine industry and to a series of policy recommendations aimed at maintaining the competitiveness of the U.S. jet engine industry. As this thesis examines only a particular sector of the aerospace industry, conclusions regarding the role of the military in developing technologies for commercial application may not necessarily apply to other sectors of the industry. Nevertheless, this research should suggest additional research into these other sectors and possibly into entirely different

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[2] These include Allied-Signal Garret Engine Division, CFE Company, General Electric Company (GE Aircraft Engines), General Motors (Allison Gas Turbine Division), Light Helicopter Turbine Engine Company, Teledyne CAE, Textron Lycoming (Stratford Division), United Technologies Pratt & Whitney, and Williams International.

industries. The argument contained in this thesis will be presented as described below.

Chapter II of this thesis reviews jet aircraft engine technology. The concepts of ideal cycle analysis are introduced and are used to develop expressions for the specific thrust and specific fuel consumption of different types of engines. These two quantities, specific thrust and specific fuel consumption, measure the thrust-generating capability and the fuel efficiency of an engine, respectively, and are two primary measures of performance for jet aircraft engines. The analysis demonstrates the dependence of these quantities upon design characteristics of and typical operating conditions for the engine.

Following this technical review, Chapter III examines the role military R&D has played in helping to establish the commercial engine industry. Particular attention is paid to the military's early interest in jet engine technology and the means by which commercial airlines later adopted the technology. In addition, this chapter reviews the development of prominent commercial engines in order to discern the influence that military research and development played in their design. The chapter ends with a several conclusions regarding the changing role of the military in commercial engine development and the reasons for the successful transfer of technology between the two sectors.

Chapter IV discusses likely requirements for future military and commercial engines. It reviews the primary directions of military R&D in aeronautics and discusses some of the more recent programs established by the military to meet these goals. Similarly, commercial research goals will be discussed and commercial research programs introduced. To the extent possible, the effect new engines will have on aircraft performance, will be evaluated from a technical perspective.

Chapter V investigates the technological innovations that will be necessary to meet the performance requirements presented in Chapter IV. In effect, a sensitivity analysis is conducted to explore the changes in engine performance achievable with changes in the thermodynamic cycle of representative military engines. The effects of these changes on commercial engines will then be assessed. Areas in which military research will benefit commercial engines will be noted as will areas of commercial need that are not satisfied by military research programs.

Using the results of the above analysis as its basis, Chapter VI will present several conclusions regarding the applicability of military engine R&D to commercial jet engines. Policy recommendations aimed at maintaining the competitiveness of the U.S. aircraft engine industry in light of the previous analysis will then identified and discussed.

CHAPTER II

AIRCRAFT JET ENGINES: A TUTORIAL

A complete understanding of the role technology transfer plays in the U.S. jet engine industry requires a basic understanding of jet engine technology. This chapter reviews the fundamental principles of jet engine operation. The intent is to introduce those with little or no knowledge of the technology to the key concepts and components of jet aircraft engines. Readers with a thorough knowledge of gas turbine design and analysis may find it appropriate to proceed to Chapter III.

The analysis presented in this chapter describes the primary components of jet aircraft engines and develops expressions for determining the performance of an engine given its primary design parameters and desired operating conditions. Throughout this analysis performance is measured in terms of specific thrust and specific fuel consumption (SFC). Specific thrust is defined as the ratio of an engine's thrust to the mass flow of air that must pass through the engine in order to generate that level of thrust. It is typically expressed in terms of pounds of thrust generated per pound mass of air per second (lbt/lbm/s). Specific thrust is of importance in determining the size of the engine required to produce a desired thrust level. Engines with a higher specific thrust can generate a given level of thrust with a smaller air mass flow than can engines with lower specific thrust. Thus, for a given level of thrust, the engine with higher specific thrust can be made smaller than an engine with low specific thrust.

Specific fuel consumption (SFC) measures the fuel efficiency of an engine. It is a measure of the number of pounds of fuel required per hour to generate a pound of thrust. Hence its units are pounds-of-fuel per pound-of-thrust per hour (lb/lbt/hr). The lower the SFC of an engine, the more fuel efficient is that engine. At a given thrust level, the engine with a lower SFC will burn less fuel per hour of flight and thus will have a greater maximum range than the same aircraft powered by an engine with a higher SFC.

A. Background:

Jet aircraft engines fall into three general categories: turbojets, turbofans, and turboprops. Most military aircraft and large commercial transports use turbojet or, to a greater extent, turbofan engines. All three of these engine types operate using similar gas generating cores. The core consists of five primary parts: an inlet or diffuser, a compressor, a burner or combustor, a turbine, and an exit nozzle. The inlet captures the incoming airstream and directs it into the compressor. Here the air is compressed, increasing its pressure and temperature for more efficient combustion. The air is then mixed with fuel and combusted in the burner section. The temperature of the gas increases dramatically during combustion, but its pressure rises only slightly as the combusted fuel-air mixture expands through a turbine section where power is extracted from the airflow to drive the compressor stage. In passing through the turbine the pressure and temperature of the gas are therefore reduced. Finally, the air is expelled through an exhaust nozzle that returns the airflow to ambient pressure though at a temperature somewhat higher than ambient temperature and a velocity higher than that of the incoming airstream.

The difference between turbojet, turbofan, and turboprop (or propfan) engines derives from the way they transform the thermal energy of the combusted fuel-air mixture into propulsive power for the aircraft. The turbojet and turbofan both rely on the increased velocity of the exhaust stream to provide a propulsive force. However, a turbojet accelerates a small quantity of air to high velocity while a turbofan produces thrust by accelerating a larger quantity of air to a lower overall velocity. A turboprop, on the other hand, uses most of the energy generated by the engine to drive a propeller which accelerates an even larger mass of air to lower velocities than the turbofan engine.

The efficiency with which an engine converts thermal energy into propulsive energy is referred to as overall engine efficiency, designated by the Greek symbol eta, η_o. Overall engine efficiency is the product of the engine's thermal efficiency, η_t, and its propulsive efficiency, η_p. The thermal efficiency is defined as the fraction of total heat energy in the fuel that is converted to work. If the work produced by the system is measured by the change in momentum of the mass air flow as it passes through the engine, the expression for thermal efficiency becomes (Boeing, 1969, p. 2-18):

$$\eta_t = \frac{\dot{m}(u_e^2 - u_0^2)}{2Jh\dot{m}_f g} \tag{2-1}$$

where: $\dot{m}$ = mass flow rate of air in lb/s
$\dot{m}_f$ = mass flow rate of fuel in lb/s
u_e = velocity of the mass flow at the exit to the engine
u_0 = velocity of the mass flow at the engine inlet (flight velocity)
J = mechanical equivalent of heat in ft-lb/BTU
h = heating value of the fuel in BTU/lb

As can be seen from this expression, the thermal efficiency of an engine increases as the exit velocity of the air stream increases or as the mass flow rate of fuel needed to produce a given exit velocity decreases. The maximum thermal efficiency available from an engine, however, is determined by the thermal capability of the engine materials. The value of the maximal thermal efficiency for an engine with a maximum possible temperature of T_m is given by a Carnot cycle operating between atmospheric temperature (the heat sink) and the maximum temperature (Kerrebrock, 1977, p. 2):

$$\eta_{t_{max}} = 1 - \frac{T_0}{T_m} \tag{2-2}$$

Propulsive efficiency, on the other hand is measured by the ratio of mechanical work done on the airplane to the mechanical work produced by the engine. The former is equal to the thrust of the engine multiplied by the flight velocity. The latter is equal to the increase in kinetic energy of the air stream. Using the notation introduced above, this can be written:

$$\eta_p = \frac{\dot{m}(u_e - u_0)u_0}{\dot{m}\left(\frac{u_e^2}{2} - \frac{u_0^2}{2}\right)} = \frac{2u_0}{(u_e + u_0)} \tag{2-3}$$

Propulsive efficiency decreases as the ratio of exhaust velocity to flight (inlet) velocity increases. As will be shown, the specific thrust of an engine increases with the ratio of inlet to exhaust velocity. Thus, in engine design, a tradeoff must be made between propulsive efficiency and thrust.

B. Ideal Cycle Analysis

A common and simple way of analyzing the performance of an aircraft engine is through "ideal cycle analysis" (Kerrebrock, 1977; Mattingly, 1987). In this methodology, the components of the engine are modeled as black boxes; each component is described not in physical terms such as its size or mass, but rather by the change it imparts on the air stream. Typically, these changes are expressed in terms of pressure and temperature ratios.

1. Stagnation Temperature and Pressure

The temperature ratios used in the analysis are not expressed in terms of actual temperatures, but in terms of "Total" or "Stagnation" temperatures, noted by a subscript "T" as in T_T. The total temperature represents the temperature that the gas would achieve if all its kinetic energy were converted to heat energy as occurs when the gas stagnates at the entrance to any of the stages of a turbine engine.

The total temperature is defined by the energy equation:

$$C_p T_T = C_p T + \frac{u^2}{2} \tag{2-4}$$

where C_p equals the specific heat of the air at constant pressure; T refers to the temperature of the gas (air in this case), and *u* refers to the velocity of the air stream (typically the flight velocity of the aircraft). In addition, the speed of sound in air, or Mach number, can be defined as follows:

$$M = \frac{u}{\sqrt{\gamma R T}} \tag{2-5}$$

where γ is defined as the ratio of the specific heat of the air at constant pressure (C_p) to the specific heat of air at constant volume (C_v) and *R* is the gas constant which relates the pressure and volume of a mass of air to its volume. For air, R has the value 0.287 kJ/kgK. Using this definition in equation 2-1 above, the equation for total temperature can be rewritten as follows:

$$T_T = T\left(1 + \frac{\gamma-1}{2} M^2\right) \tag{2-6}$$

A similar expression can be derived for the total pressure of a gas. This expression makes use of the relationship between the change in pressure and the change in temperature for an ideal gas undergoing adiabatic expansion or compression (i.e., expansion or compression with no transfer of heat energy into or out of the system). Under such conditions, the total pressure is related to the total temperature of the gas by the relation:

$$\frac{P_T}{P} = \left(\frac{T_T}{T}\right)^{\frac{\gamma}{\gamma-1}} \tag{2-7}$$

Substituting equation 2-3 into this expression yields the following result:

$$P_T = P\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{2-8}$$

2. Temperature and Pressure Ratios:

Ideal cycle analysis uses special notation to refer to ratios of temperatures and pressures. With this nomenclature, the greek letter τ represents a ratio of total temperatures; the Greek letter π represents a ratio of total pressures; Θ represents the ratio of total temperature to atmospheric (ambient) temperature; and δ represents the ratio of total pressure to atmospheric (ambient) pressure. For example, the total pressure ratio across the compressor can be written π_C and the stagnation temperature of the ambient air can be written Θ_0.

3. Assumptions of Ideal Cycle Analysis:

Ideal cycle analysis makes three primary assumptions regarding the thermodynamic cycles of the jet engine:

- All expansion and compression of gases is <u>isentropic</u>.
  Thus, the temperature and pressure of a gas before and after compression or expansion are related by equation 2-7 above.
- All combustion occurs at <u>constant total pressure</u> (π_B = 1).
- The exit nozzle provides <u>perfect expansion</u>.
  Thus the pressure of the gas at the exit of the engine nozzle is equal to atmospheric pressure.

These assumptions greatly simplify the analysis of the jet engine. At the same time, they provide an accurate description of the engine. Many of the non-ideal effects of the engine not accounted for in this model tend to counteract one another using the above assumptions.

More precise estimates of engine parameters can be calculated by taking deviations from the ideal behavior into account. Of particular interest are the turbine and compressor stage "polytropic" efficiencies. If such effects are included in the cycle analysis, the expressions for specific thrust and SFC become extremely complex and cannot easily be written as single equations; rather, they must be solved in parts. Thus, the effects of component inefficiencies will not be addressed in this chapter, although later analyses of engines will take such factors into account. A derivation of the cycle analysis equations for non-ideal components can be found in several references including Mattingly (1987) and Oates (1988).

C. Turbojet Engine Analysis

This section applies ideal cycle analysis to the turbojet engine. A block diagram of a generic turbojet is depicted in Figure 2-1. As shown, the turbojet consists of five major components: the inlet or diffuser (D), the compressor (C), the combustor or burner (B), the turbine (T), and the exit nozzle (N).

1. Turbojet Notation:

Station numbers are assigned to these components as shown in the figure. These station numbers are used as subscripts in the ideal cycle analysis. Using the standard notation, station 0 refers to ambient conditions far enough away from the engine as to be unaffected by the engine's presence. At this point ambient conditions are defined as T_0, P_0, and u_0 where u refers to the velocity of the airstream. Station 1 refers to the entrance to the diffuser at which point the air mass flow, $\dot{m}$, enters the engine. Stations 2 and 3 refer to the entrance and exit to the compressor, respectively. Stations 4 and 5 refer to the entrance and exit to the turbine, and stations 6 and 7 refer to the entrance and exit to the nozzle. (Alternatively, stations 3 and 4 can be considered the entrance and exit of the combustor). Based upon the assumptions of ideal cycle analysis, the pressure of the air flow at station 7 is assumed to be equal to P_0.

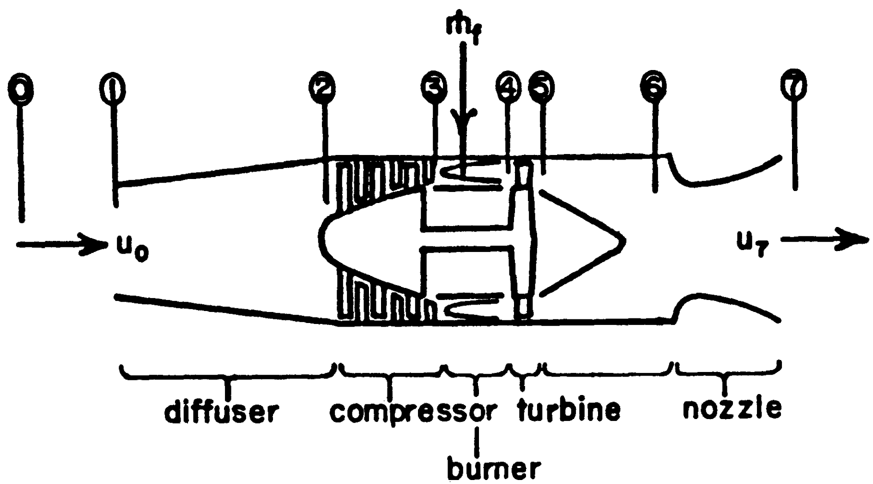

Figure 2-1

Schematic Diagram of a Turbojet Engine Showing Primary Components and Station Numbers. [From Kerrebrock (1977, p. 6)]

Additional subscripts will be used in this analysis to refer to pressure or temperature ratios across a component. The subscript *D* will be used to refer to ratios across the diffuser, or similarly, between stations 1 and 2. The subscript *C* will refer to ratios across the combustor; *B* will refer to ratios across the burner; *T* will refer to ratios across the turbine; and *N* will refer to ratios across the nozzle.

2. General Expression for Thrust:

The thrust of a turbine engine is defined as the force resulting from the change in momentum of the air as it flows through the engine (Kerrebrock, 1977, p. 14). Thus, engine thrust is actually the net thrust imparted to the airflow. This thrust is governed by Newton's Third Law of Motion which in its simplest form can be stated:

$$F = ma \tag{2-9}$$

When applied to mass flows defined in terms of mass per unit time, this expression can be written in terms of $\dot{m}$ which is defined as du/dt. If one neglects the mass of fuel added to the air passing through the engine, the thrust of the turbojet can be rewritten using this notation as follows:

$$F = \dot{m}(u_7 - u_0) \tag{2-10}$$

in which u_7 and u_0 are defined as the velocity of the air stream at the exit and entrance of the nozzle, respectively. If we let the symbol "*a*" represent the local speed of sound given the local conditions of temperature, pressure, and density, this expression can be written in terms of the local Mach number of the airflow as it passes through the engine:

$$F = \dot{m}(a_7 M_7 - a_0 M_0) \tag{2-11}$$

Recalling the definition of Mach number presented in equation 2-5, equation 2-11 becomes:

$$F = a_0 M_0 \dot{m} \left(\sqrt{\frac{T_7}{T_0}} \frac{M_7}{M_0} - 1 \right) \tag{2-12}$$

Typically, engines are rated in terms of their "specific thrust", the ratio of their total thrust to the mass flow rate required to generate that thrust. Specific thrust describes the change in velocity of the total airflow after is has been accelerated by the engine. It is therefore a direct measure of an engine's ability to generate thrust at a given mass flow rate. In this sense, specific thrust is a better measure of an engine's performance capabilities than is simply thrust because specific thrust relates thrust to the required mass airflow--and hence to the size of the engine required to produce the thrust. Using this convention, equation 2-9 can be written:

$$\frac{F}{\dot{m}} = a_0 M_0 \left[\sqrt{\frac{T_7}{T_0}} \frac{M_7}{M_0} - 1 \right] \tag{2-13}$$

As expression 2-13 indicates, the specific thrust of an engine is a function primarily of the temperature and Mach number ratios across the engine; the remainder of the ideal cycle analysis therefore focuses on deriving expression for these relations.

Using the definition of stagnation temperature presented earlier, the expression for the total temperature at station 7 becomes:

$$T_{T_7} = T_7\left(1 + \frac{\gamma-1}{2} M_7^2\right) \tag{2-14}$$

The stagnation temperature at station 7 can also be computed by considering the piece-wise change in temperature as the air traverses through the different components of the engine. Using this approach:

$$T_{T_7} = T_0 \theta_0 \tau_C \tau_B \tau_T \tau_N \tag{2-15}$$

The last term in this equation is equal to zero in ideal cycle analysis because the nozzle is assumed to provide perfect expansion of the gas. By equating equations 2-14 and 2-15, the following relation can be generated:

$$\frac{T_7}{T_0} = \frac{\theta_0 \tau_C \tau_B \tau_T}{\left(1 + \frac{\gamma-1}{2} M_7^2\right)} \tag{2-16}$$

Similar expressions can be written for the total pressure of the gas at station seven. Using the definition of total pressure:

$$P_{T_7} = P_7\left(1 + \frac{\gamma-1}{2} M_7^2\right)^{\frac{\gamma-1}{\gamma}} \tag{2-17}$$

By tracing the flow of the gas through the engine and accounting for the change in pressure at each stage, the following expression can be derived:

$$P_{T_7}=P_0\delta_0\pi_C\pi_B\pi_T\pi_N \tag{2-18}$$

Again, by the assumptions of the ideal cycle analysis, the total pressure ratio across the burner and the total pressure ratio across the nozzle are equal to one. In addition, the analysis assumes that the nozzle expands the gas to atmospheric pressure, P_0. Thus, equations 2-17 and 2-18 can be equated and the P_0 and P_7 terms cancel each other out. The resulting expression takes the form:

$$1+\frac{\gamma-1}{2}M_7{}^2=(\delta_0\pi_C\pi_T)^{\frac{\gamma}{\gamma-1}} \tag{2-19}$$

The left-hand side of this equation is identical to the denominator in equation 2-16. Thus, the right-hand side of this equation can be substituted into equation 2-16 to produce the following relation:

$$\frac{T_7}{T_0}=\frac{\theta_0\tau_C\tau_B\tau_T}{(\delta_0\pi_C\pi_T)^{\frac{\gamma-1}{\gamma}}} \tag{2-20}$$

The denominator of this expression, however, is simply the pressure relationship for an isentropic temperature ratio, as shown earlier in equation 2-7. In other words:

$$(\delta_0\pi_T\pi_T)^{\frac{\gamma-1}{\gamma}}=\theta_0\tau_C\tau_T \tag{2-21}$$

Thus, equation 2-21 reduces to:

$$\frac{T_7}{T_0}=\tau_B \tag{2-22}$$

With this expression in hand, the remaining task is to calculate the Mach number ratio across the engine. This can be accomplished by combining equations 2-19 and 2-21. By substituting the right-hand side of equation 2-21 into 2-19 and manipulating the result to isolate M_7^2, the equation becomes:

$$M_7^2 = \frac{2}{\gamma-1}(\theta_0 \tau_C \tau_T - 1) \tag{2-23}$$

Similarly,

$$M_0^2 = \frac{2}{\gamma-1}(\theta_0 - 1) \tag{2-24}$$

Thus,

$$\frac{M_7}{M_0} = \sqrt{\frac{\theta_0 \tau_C \tau_T - 1}{\theta_0 - 1}} \tag{2-25}$$

The equation for specific thrust can be found by substituting the expressions for the temperature ratio and the Mach number ratio into the general thrust equation. The result is shown below:

$$\frac{F}{\dot{m}} = M_0 a_0 \left[\left\{\frac{\tau_B(\theta_0 \tau_C \tau_T - 1)}{\theta_0 - 1}\right\}^{\frac{1}{2}}\right] - 1 \tag{2-26}$$

3. Turbine-Compressor Power Balance for the Turbojet:

The specific thrust equation for the turbojet can be further simplified by considering the power relationship between the turbine and the compressor. Because all the power that the turbine extracts from the gas is used to drive the compressor, the compressor power and the turbine power must be equal. The power balance can be expressed solely in terms of heat energy extraction if total temperatures are used. In this form the power balance is expressed as:

$$\dot{m} C_p (T_{T_3} - T_{T_2}) = (\dot{m} + \dot{m}_f) C_p (T_{T_4} - T_{T_5}) \tag{2-27}$$

where $\dot{m}_f$ is the mass flow of fuel into the combustor. Because this flow is small compared to the mass air flow, the mass flow of fuel can be neglected in this analysis. Manipulation of equation 2-27 yields the following expression:

$$\frac{T_{T_2}}{T_0} \left(\frac{T_{T_3}}{T_{T_2}} - 1 \right) = \frac{T_{T_4}}{T_0} \left(1 - \frac{T_{T_5}}{T_{T_4}} \right) \tag{2-28}$$

The terms of this expression can be further simplified by noting their relationship to variables defined earlier. With proper substitution, Equation 2-28 becomes:

$$\tau_T = 1 - \frac{\theta_0}{\theta_T} (\tau_C - 1) \tag{2-29}$$

The right hand side of this expression can then be substituted into the specific thrust equation derived above to yield the following expression:

$$\frac{F}{\dot{m}} = M_0 a_0 \left[\left\{ \left(\frac{\theta_0}{\theta_0 - 1} \right) \left(\frac{\theta_T}{\theta_0 \tau_C} - 1 \right) (\tau_C - 1) + \frac{\theta_T}{\theta_0 \tau_C} \right\}^{\frac{1}{2}} - 1 \right] \tag{2-30}$$

Further simplification is not possible. The above expression, though complex, defines the specific thrust of the turbojet in terms of only four variables. Two of these are the design operating conditions for the engine, θ_0 and M_0 which are defined by the altitude at which the aircraft engine operates. The other two variables, θ_T and π_C, are design variables determined by the design of the engine. The former defines the maximum allowable turbine inlet temperature (TIT) of the engine. This value is a function of the turbine materials and cooling system. Thus, maximum turbine inlet temperature is determined by the state-of-the-art in turbine materials and cooling system design. The second defines the compression ratio of the engine. Greater flexibility is possible with compression ratio as additional compressor stages can be added to an engine to increase its compression ratio. In practical applications, though, maximum compression ratio is limited by weight considerations.

4. Specific Fuel Consumption:

Specific fuel consumption (SFC) is a measure of the fuel efficiency of a turbine engine. It expresses the number of pounds of fuel used per hour to generate a pound of thrust. Its units are therefore lb/lbt/hr. By definition:

$$SFC = \frac{g\,\dot{m}_f}{F}(3600) = \frac{g\,\dfrac{\dot{m}_f}{\dot{m}}}{\left(\dfrac{F}{\dot{m}}\right)}(3600) \qquad \text{(2-31)}$$

where F equals the thrust of the engine (in pounds) and *g* is acceleration due to gravity (approximately 32.1 ft/s^2). The 3600 factor converts the SFC calculation from seconds to hours.

SFC is computed by considering the energy balance across the combustor. As no other energy is put into the system, this balance can be expressed as:

$$\dot{m}\,C_p\,(T_{T_4} - T_{T_3}) = \dot{m}_f\,h \qquad \text{(2-32)}$$

where *h* is the heating value of the fuel measured in BTU/lb. For typical jet engine fuel, h = 18,500 BTU/lb. In simple terms, this equation states that the heat energy added to the airstream (the right-hand side of the equation) produces a change in the energy of the airstream proportional to the change in total temperature of the gas across the combustor.

This equation can be solved for the ratio of $\dot{m}_f/\dot{m}$ in the following manner:

$$\frac{\dot{m}_f}{\dot{m}} = \frac{C_p T_0}{h}\left[\frac{T_{T_4}}{T_0} - \left(\frac{T_{T_3}}{T_{T_2}}\right)\left(\frac{T_{T_2}}{T_0}\right)\right] \qquad \text{(2-33)}$$

$$\frac{\dot{m}_f}{\dot{m}} = \frac{C_p T_0}{h}(\theta_T - \tau_C \theta_0) \qquad \text{(3-34)}$$

By substituting this last expression into equation 2-31, SFC can be expressed in the following terms:

$$SFC = \left(\frac{C_p T_0 g}{h}\right)\left(\frac{1}{F/\dot{m}}\right)(\theta_T - \tau_C \theta_0)(3600) \qquad \text{(2-35)}$$

5. Typical Turbojet Performance:

The equations for specific thrust and specific fuel consumption derived above can be used to explore the performance of a turbojet engine given values of the two design variables, maximum turbine inlet temperature and compression ratio, and the design operating conditions of the engine, namely altitude and velocity.

The effect of design flight velocity is shown in Figure 2-2. This graph was plotted using equation 2-30 assuming a constant flight altitude of 30,000 feet, a compression ratio of 24, and a turbine inlet temperature of 2900° Rankine (R) which at 30,000 feet corresponds to a θ_T of 7. Flight velocity was varied between Mach 0 and Mach 2.5. As shown, the specific thrust of the engine declines monotonically with increasing Mach number. This effect is the result of the increasing velocity of the incoming airstream at higher flight speeds. As the velocity of the incoming velocity increases, the ratio of the exhaust velocity to the inlet velocity decreases, lowering the specific thrust of the engine.

The graph can also be used to determine the airflow required at a given flight velocity to generate a desired level of thrust. For example, at Mach 1.0, the specific thrust of the engine is approximately 87 lbt/lbm/s. Thus, an engine designed for operation a Mach 1.0 will generate 8700 pounds of thrust with an airflow of 100 lbm/s or 17,400 pounds of thrust with an airflow of 200 lbm/s. The desired thrust level will therefore affect the required airflow and hence the size of the engine.

The effect of increasing flight velocity on SFC is shown in Figure 2-3. Between Mach numbers of 0 and 1.9, the SFC of the engine increases because the energy required to produce a given change in velocity from inlet to exhaust increases with flight speed. Above Mach 1.9, however, SFC actually declines with increasing flight speed because both the thermal and propulsive efficiencies of the

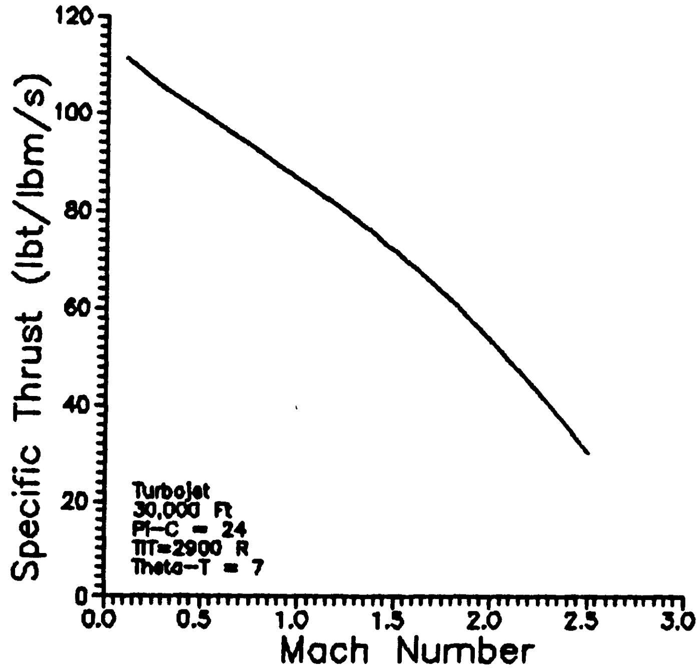

Figure 2-2

Variation in Specific Thrust of a Turbojet Engine with Flight Mach Number.

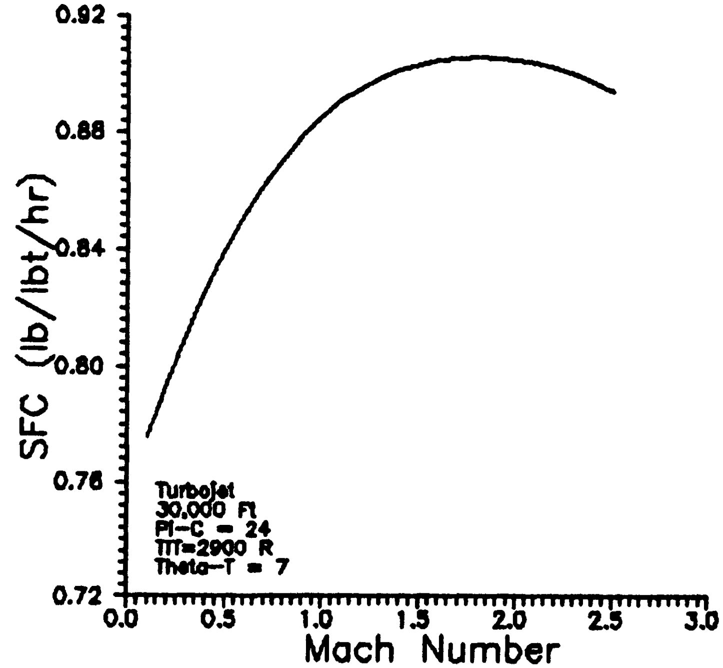

Figure 2-3

Variation in Specific Fuel Consumption of a Turbojet Engine with Flight Mach Number.

engine are increased by the higher airstream velocity at the inlet.

Changes in turbine inlet temperature and compression ratio also influence the specific thrust and SFC of a turbojet engine. The effect of these design variables upon specific thrust is shown in Figure 2-4. This graph plots the specific thrust versus compression ratio for a turbojet designed to operate at Mach 0.8 at 30,000 feet. Performance is plotted for three different turbine inlet temperatures, 2600°, 2900°, and 3200°R. As the graph demonstrates, specific thrust increases with increasing turbine inlet temperature. In the case shown here, each 300°R increases in TIT boosts the specific thrust of the engine by over 10% for compression ratios above 10. The effect of compression ratio upon specific thrust is more complicated. At each turbine inlet temperature, an optimal compression ratio exists at which specific thrust achieves its maximum value. This value can be calculated by differentiating equation 2-30 with respect to τ_T, setting the result equal to zero, and solving for τ_C. By doing so, it can be shown that specific thrust is optimized when τ_T equals $\sqrt{\Theta_T}/\Theta_0$. The optimal π_C can then be calculated from the adiabatic relationship between temperature and pressure, equation 2-7.

The effect of turbine inlet temperature and compression ratio upon SFC is shown in Figure 2-5. Again, curves are plotted for three different values of TIT. As shown, the SFC of a turbojet engine increases with increasing TIT. This increase results from the higher velocity at which the airstream is exhausted from the engine at higher temperatures. SFC can be reduced at all turbine inlet

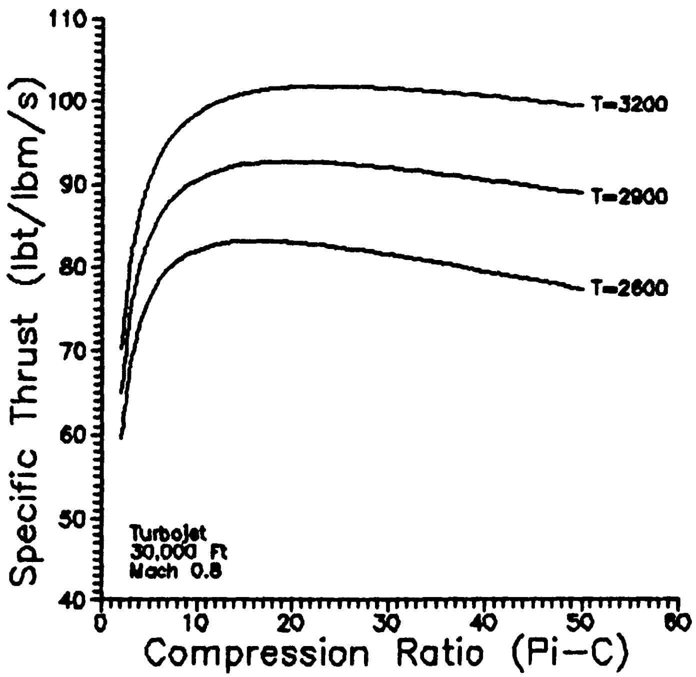

Figure 2-4

Variation in Specific Thrust of a Turbojet Engine with Compression Ratio for Three Different Turbine Inlet Temperatures.

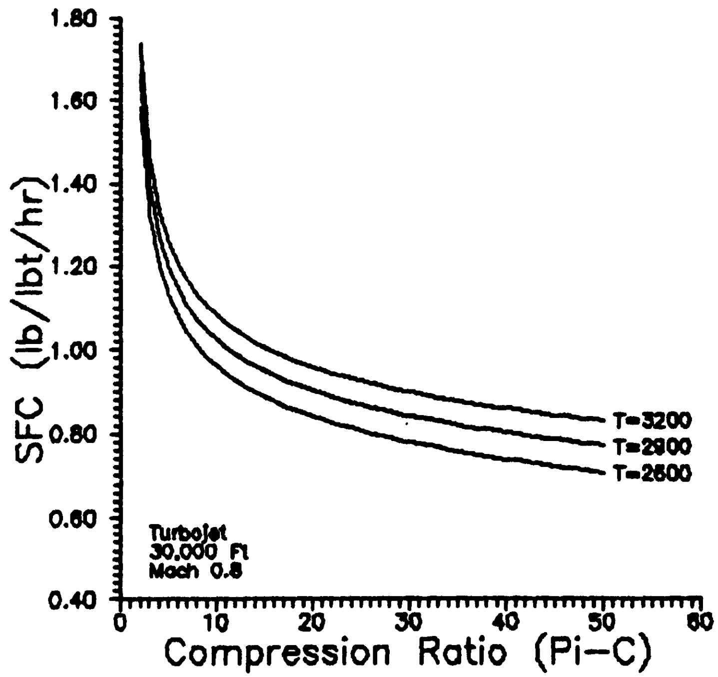

Figure 2-5

Variation in Specific Fuel Consumption of a Turbojet Engine with Compression Ratio for Three Different Turbine Inlet Temperatures.

temperatures by increasing the compression ratio of the engine. The higher compression ratio improves the efficiency of the engine cycle and thereby reduces SFC.

D. Turbofan Engine Analysis

The propulsive efficiency of a jet engine can be greatly improved by using a fan to pump air through a secondary nozzle. The fan section is powered by a second turbine placed downstream of the compressor turbine. In this manner, a portion of the energy contained in the primary jet (or core stream) is transferred to the fan stream. The engine accelerates a larger mass of air to a smaller velocity than a turbojet, improving its propulsive efficiency. This configuration is called a "turbofan" engine.

1. Turbofan Notation:

Figure 2-6 depicts schematically a turbofan engine. The turbofan cycle differs from the turbojet cycle in that two air mass flows must be considered, the core mass flow, designated $\dot{m}_{core}$, and the "bypass" air mass flow, designated $\dot{m}_{fan}$. The bypass ratio of the engine is defined as the fraction of air in the bypass stream to the air in the core stream. It is designated by the greek letter α. Hence:

$$\alpha \doteq \frac{\dot{m}_{fan}}{\dot{m}_{core}} \tag{2-36}$$

As shown, the turbofan station numbers are similar to those of the turbojet. Station 0 represents the ambient conditions; station 1 refers to the inlet; station 2

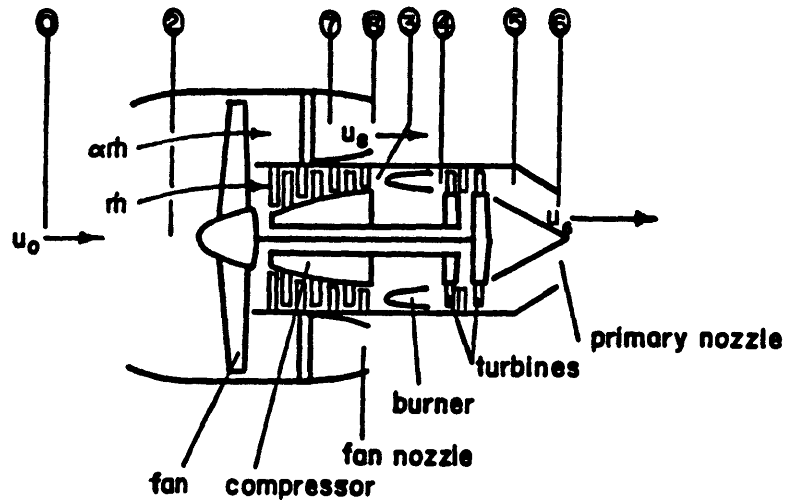

Figure 2-6

Schematic Diagram of a Turbofan Engine Showing Primary Components and Station Numbers. [From Kerrebrock (1977, p. 8)]

to the entrance to the fan/compressor. As with the turbojet, station 3 is the compressor exit or burner entrance, and station 4 is the burner exit or turbine entrance. Station 5 is then defined as the turbine exit and entrance to the core stream nozzle; station 6 is the exit of the core stream nozzle. Station 7 is the entrance to the bypass stream nozzle; and station 8 is the exit of the bypass stream nozzle.

The equations for the turbofan are identical to those for the turbojet until the turbine-compressor power balance is considered.

2. Turbofan Power Balance:

For the turbofan, the power balance must consider not only the power extracted for driving the core compressor, but must consider the power extracted for driving the fan as well. Thus, the power balance equation takes on the following form:

$$\dot{m}_{core}\, C_p(T_{T_4}-T_{T_5}) = \dot{m}_{core}\, C_p(T_{T_3}-T_{T_2})+\alpha\dot{m}_{core}\, C_p(T_{T_7}-T_{T_2}) \tag{2-37}$$

Again, this equation can be manipulated into a form in which design parameters can be recognized.

$$\frac{T_{T_4}}{T_{T_2}}\left(1-\frac{T_{T_4}}{T_{T_5}}\right) = \left(\frac{T_{T_3}}{T_{T_2}}-1\right)+\alpha T_{T_2}\left(\frac{T_{T_7}}{T_{T_2}}-1\right) \tag{2-38}$$

$$\tau_T = 1-\left(\frac{\theta_0}{\theta_T}\right)\left((\tau_C-1)+\alpha(\tau_F-1)\right) \tag{2-39}$$

For the turbofan, total thrust of the engine is the sum total of the thrusts generated by the core stream and the fan stream. The equation for the thrust of the fan stream is analogous to that for the core stream derived for the turbojet, except that τ_C is replaced by τ_F, and τ_B and τ_T are replaced by unity. Thus, the total specific thrust of the turbojet can be written:

$$\frac{F}{\dot{m}} = M_0 a_0\left[\sqrt{\left(\frac{\theta_T}{\theta_0\tau_C}\right)\left(\frac{\theta_0\tau_C\tau_T-1}{\theta_0-1}\right)}-1\right]+\alpha M_0 a_0\left[\sqrt{\frac{\theta_0\tau_F-1}{\theta_0-1}}-1\right] \tag{2-40}$$

3. Turbofan Optimization:

The advantage of the turbofan lies in its ability to utilize the kinetic energy of the core air stream to accelerate a large mass of air in the bypass stream. As a result, the total mass of air accelerated in a turbofan engine is increased while the velocity of the core exhaust is reduced. By trading a high exhaust velocity for a high mass flow, the turbofan can achieve an improvement in propulsive efficiency relative to the turbojet[1]. For a given engine core, the velocity of the core airflow will be a function of the bypass ratio. Larger bypass ratios will further decrease the core stream velocity; conversely, they will increase the velocity of the bypass flow. The bypass ratio at which the two streams have the same velocity will therefore be the optimal operating point for the engine.

The engine will be operating optimally in terms of overall efficiency when

$$u_{core\ exhaust} = u_{fan\ exhaust} \tag{2-41}$$

The velocities of airflow at the core and fan exhausts are given by the terms under the square root in equation 2-40. Thus, the condition that the two exhaust streams have equal velocity can be evaluated by setting these two terms equal subject to τ_T having the value defined by equation 2-39. Thus,

$$\frac{\theta_T}{\theta_0 \tau_C}\left(\frac{\theta_0 \tau_C \tau_T - 1}{\theta_0 - 1}\right) = \frac{\theta_0 \tau_F - 1}{\theta_0 - 1} \tag{2-42}$$

This equation can then be solved for τ_F, yielding the following expression:

$$\tau_F = \frac{1 + \theta_T + \theta_0(1 + \alpha - \tau_C) - \left(\frac{\theta_T}{\theta_0 \tau_C}\right)}{\theta_0(1 + \alpha)} \tag{2-43}$$

[1]The improvement in propulsive efficiency relative to the turbojet engine depends on the air speeds at which the engines are operating.

Substituting this result into equation 2-37, the specific thrust of the turbofan--in terms of the total mass air flow--can be written:

$$\frac{F}{\dot{m}(1+\alpha)} = M_0 a_0 \left[\sqrt{\frac{\theta_T - \left[\frac{\theta_T}{\theta_0 \tau_C}\right] - \theta_0(\tau_C - 1) + \alpha(\theta_0 - 1)}{(\theta_0 - 1)(1+\alpha)}} - 1 \right] \tag{2-44}$$

In this form, the expression for specific thrust is a function of only three design variables: α, the bypass ratio; τ_C which is a function of the compression ratio; and θ_T, the normalized turbine inlet temperature.

4. Turbofan Energy Balance:

As with the turbojet, the turbofan specific fuel consumption can be determined from an energy balance across the combustor. As heat energy is added only to the core stream, the energy balance takes the same form as with the turbojet. Hence,

$$SFC = \left[\frac{C_P T g}{h}\right]\left[\frac{1}{F/\dot{m}(1+\alpha)}\right]\left[\frac{\theta_T - \theta_0 \tau_C}{(1+\alpha)}\right](3600) \tag{2-45}$$

5. Typical Turbofan Performance:

Using equations 2-44 and 2-45, the performance of the turbofan engine as a function of its design variables and operating conditions can be explored. Figure 2-7 shows the relationship between specific thrust and design Mach number for a turbofan engine that operates at 30,000 feet with a bypass ratio of 1, an overall (fan plus compressor) pressure ratio of 30, and a turbine inlet temperature of 2900°R. As with the turbojet, specific thrust declines with increasing Mach number. By comparing this graph with that in Figure 2-2, one can also see that the specific thrust of the turbofan is less than that of the turbojet at all Mach numbers. The lower specific thrust results from the fact that the energy generated in the core is used to accelerate both the bypass airstream and the core airstream. The advantage of this design is that the propulsive efficiency of the engine, and hence its SFC is improved compared to the turbojet.

This effect is demonstrated in Figure 2-8 which plots the SFC of the turbofan engine described above versus flight Mach number. As shown, the SFC of this engine increases monotonically with Mach number over the region explored. However, the SFC of this engine is less than that of the turbojet throughout this range. For example, at Mach 1.0, the SFC of the bypass turbofan is about 0.69 lb/lbt/hr compared to 0.88 for the turbojet.

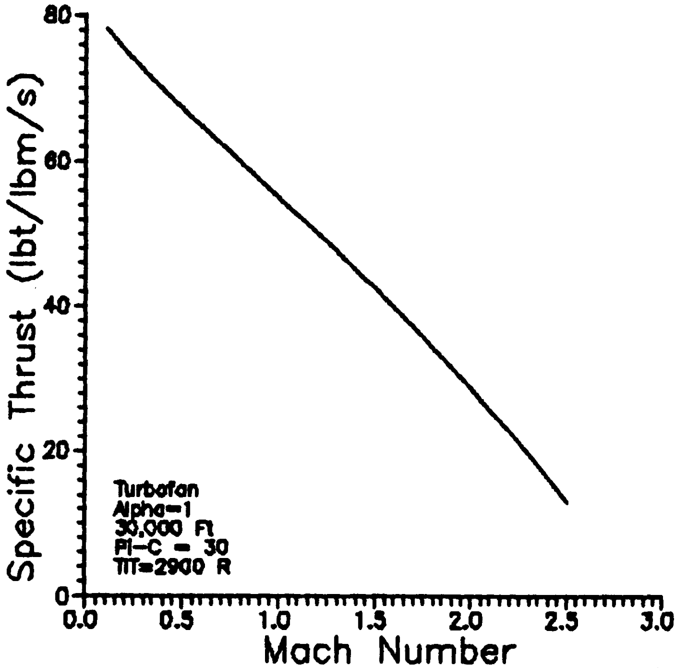

Figure 2-7

Variation in Specific Thrust of a Turbofan Engine with Flight Mach Number.

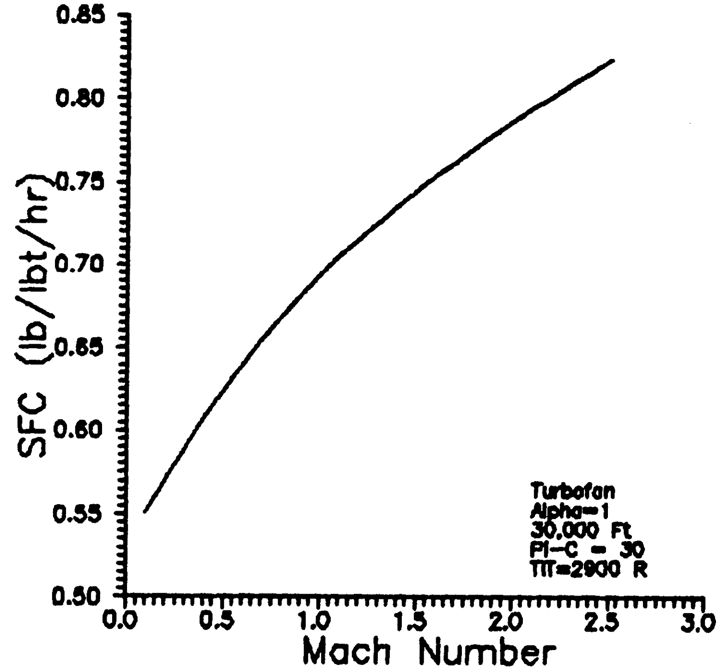

Figure 2-8

Variation in Specific Fuel Consumption of a Turbofan Engine With Flight Mach Number.

Further increases in bypass ratio will tend to lower both the specific thrust and the SFC of a turbofan engine. This effect is demonstrated in Figures 2-9 and 2-10 which plot the specific thrust and SFC, respectively, for a turbofan engine operating at Mach 0.8 at an altitude of 30,000 feet. Compression ratio is assumed to be constant at 30, and the turbine inlet temperature is held constant at 2900° while bypass ratio is varied between 0 (a straight turbojet) and 20 (an "ultra-high bypass" turbofan). As shown, both specific thrust and SFC drop off rapidly as the bypass ratio is increased from 0 to 5 and continue to decline, though at a slower rate, as bypass ratio is increased to 20. As these graphs indicate, a tradeoff must therefore be made between specific thrust and SFC in turbofan engine design.

E. Afterburning

Engine thrust can be further increased by adding additional fuel to the airflow and combusting it downstream of the turbine in an "afterburner". Though this process increases the SFC of the engine significantly, it can greatly augment the thrust of the engine and is useful in providing for short bursts of high thrust for supersonic dash capability in aircraft. Afterburning is made possible by the fact that combustion in the burner is limited by the thermal resistance of the turbine and as a result cannot combust all the oxygen in the air. Afterburning combusts a portion of this residual oxygen. Higher combustion temperatures can be used in an afterburner than in the combustion chamber because the surface area is small enough to permit cooling and because the hot gases do not impinge on any rotating blades.

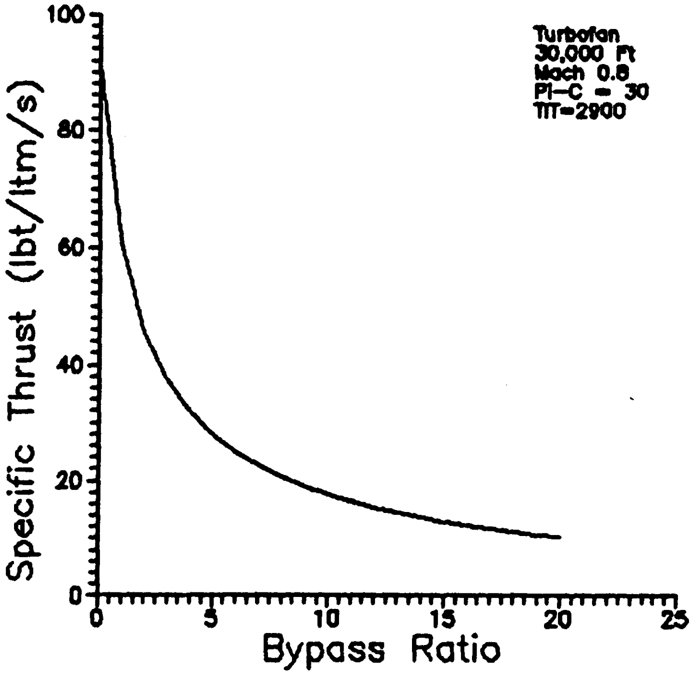

Figure 2-9

Influence of Bypass Ratio Upon the Specific Thrust of a Turbofan Engine at Mach 0.8.

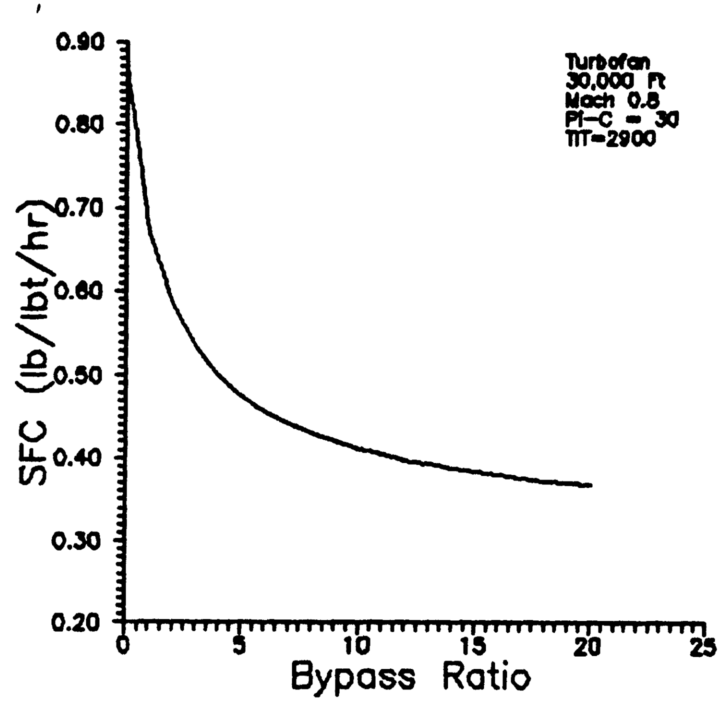

Figure 2-10

Influence of Bypass Ratio Upon the Specific Fuel Consumption of a Turbofan Engine at Mach 0.8.

1. Afterburning Turbojet:

The afterburning turbojet is shown schematically in Figure 2-11. As indicated, this engine is identical to the unaugmented turbojet except that additional fuel ($\dot{m}_a$) is to the airstream behind the turbine and is combusted. The ideal cycle analysis of this engine is identical to that for the unaugmented engine except that the temperature rise in the afterburner must be taken into account. This can be done by simply modifying the expression for specific thrust so that the term τ_B is replaced by $\tau_B\tau_A$ where τA represents the temperature rise in the afterburner, T_{T7}/T_{T5}.

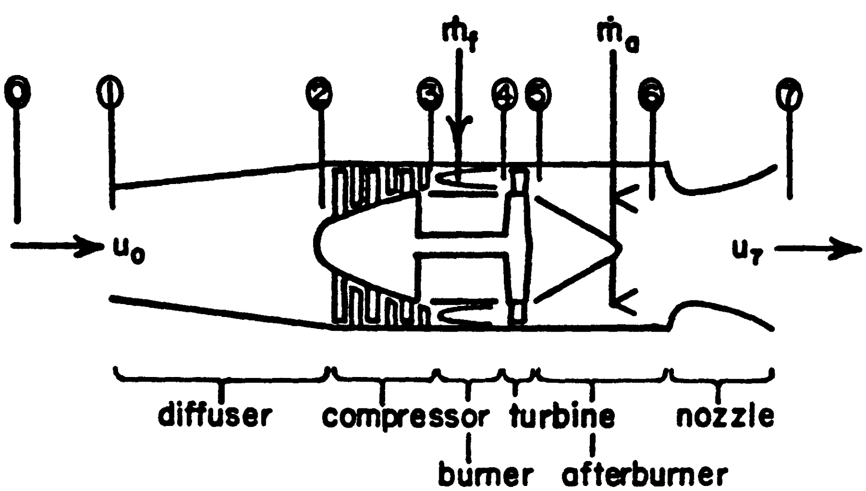

Figure 2-11

Schematic Diagram of an Afterburning Turbojet Engine.
[From Kerrebrock (1977, p. 6)]

The expression for specific thrust is more helpful if it can be expressed in terms of the normalized afterburner temperature, θ_A. This result can be achieved by making the following substitutions:

$$\tau_B = \frac{\theta_T}{\theta_0 \tau_C} \qquad \tau_A = \frac{\theta_A}{\theta_T \tau_T} \tag{2-46}$$

The resulting equation for specific thrust becomes:

$$\frac{F}{\dot{m}} = M_0 a_0 \left[\sqrt{ \left(\frac{\theta_A}{\theta_0 - 1} \right) \left(1 - \frac{\frac{\theta_T}{\theta_0 \tau_C}}{\theta_T - \theta_0 (\tau_C - 1)} \right) } - 1 \right] \tag{2-47}$$

The SFC can be determined from a power balance across the entire engine. This analysis yields:

$$\dot{m}_f + \dot{m}_a = \dot{m} \left(\frac{C_p T}{h} \right) (\theta_a - \theta_0) \tag{2-48}$$

Substituting this expression into the general equation for SFC:

$$SFC = \left(\frac{C_p T g}{h} \right) \left(\frac{1}{(F/\dot{m})} \right) (\theta_A - \theta_0)(3600) \tag{2-49}$$

2. Afterburning Turbofan:

The turbofan engine can also be modified with an afterburner to improve its specific thrust. For many aircraft with a subsonic cruise requirement and a supersonic dash requirement, the afterburning turbofan is an ideal design choice.

Figure 2-12 depicts an afterburning turbojet engine. In this type of engine, the core and bypass airflows are almost always mixed prior to afterburning. This configuration places an additional requirement on the design of the engine, specifically, the pressure ratios of the core and bypass airflows must be the same just before the afterburner. In order for P_{T5} to equal P_{T7}, the fan pressure ratio must equal the product of the compressor pressure ratio and the turbine pressure ratio. More explicitly:

$$\pi_F = \pi_C \pi_T \tag{2-50}$$

Assuming that the combustion in the afterburner brings the core and bypass streams to the same temperature, the two airstreams will also have the same exit

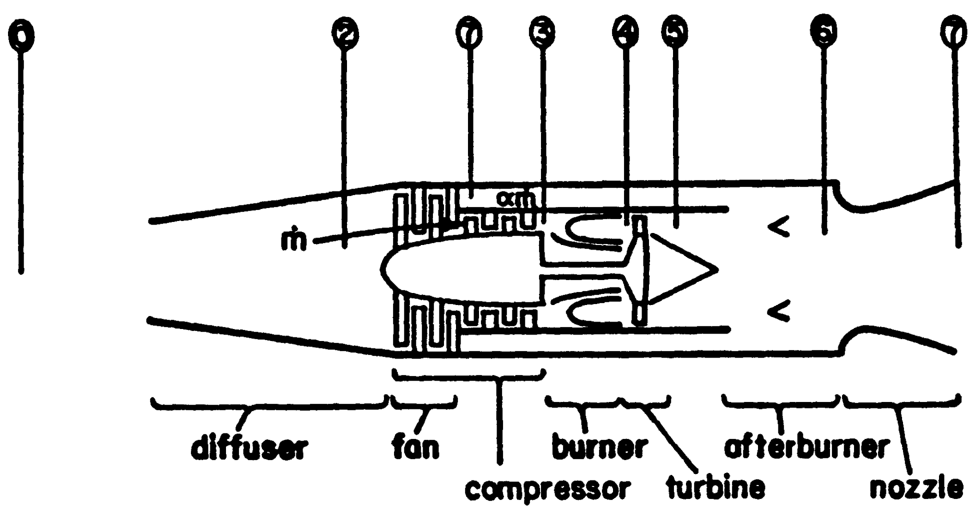

Figure 2-12

Schematic Diagram of an Afterburning Turbofan Engine. [From Kerrebrock (1977, p. 34)]

velocity (since their total pressure is also the same). Thus, the equation for specific thrust can be written as:

$$\frac{F}{\dot{m}} = (1+\alpha)\, a_0 M_0 \left[\sqrt{\left(\frac{\theta_A}{\theta_0 \tau_F}\right)\left(\frac{\theta_0 \tau_F - 1}{\theta_0 - 1}\right)} - 1 \right] \tag{2-51}$$

To meet the pressure requirements for this engine:

$$\tau_F = \frac{\theta_T + \theta_0 (1 + \alpha - \tau_C)}{\left(\dfrac{\theta_T}{\tau_C + \alpha \theta_0}\right)} \tag{2-52}$$

The SFC of the afterburning turbofan is calculated after consideration of the energy balance. Since the bypass and core air streams are brought to the same temperature in the afterburner, the energy balance can be written as:

$$\dot{m}_f h = \dot{m} (1 + \alpha) C_p T (\theta_A - \theta_0) \tag{2-53}$$

The resulting equation for SFC takes the form:

$$SFC = \left(\frac{C_p T g}{h}\right)\left(\frac{1}{F/\dot{m}}\right)(\theta_a - \theta_0)(3600) \tag{2-54}$$

The effect of afterburning on the performance of a turbofan engine is shown in Figures 2-13 and 2-14 which plot specific thrust and SFC versus flight Mach number for both non-afterburning and afterburning versions of the same engine[2]. This engine is assumed to have a bypass ratio of 1, an overall pressure ratio of 30,

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[2]The results for an afterburning turbojet engine are comparable.

and a turbine inlet temperature of 2900 which at 30,000 feet corresponds to a θ_T of 7. The afterburning engine is assumed to have a θ_A equal to 10. As Figure 2-13 shows, afterburning can increase the specific thrust of this engine by over 80 lbt/lbm/s at all flight speeds. For a given mass airflow, this increase in specific thrust would greatly increase the total net thrust of the engine. However, as shown in Figure 2-14, afterburning also increases the SFC of the engine by more than 0.40 lb/lbt/hr at all flight velocities. Thus, the range that the aircraft can fly with full afterburning power is considerably less than the range it can fly without afterburning. This effect will demonstrated in more detail later in this thesis.

The analysis presented in this chapter demonstrates the key parameters in determining the performance of turbojet and turbofan engines. For turbojet engines, performance at a given operating point is determined primarily by compression ratio and maximum turbine inlet temperature. For turbofan engines, performance is determined primarily by compression ratio, turbine inlet temperature, and bypass ratio. This insight will be used later in this thesis to explore ways of improving the performance of military and commercial engines. After determining appropriate measures of performance for the engines used on different military and commercial aircraft, the technological advances necessary to achieve the improved performance goals will be investigated through ideal cycle analysis.

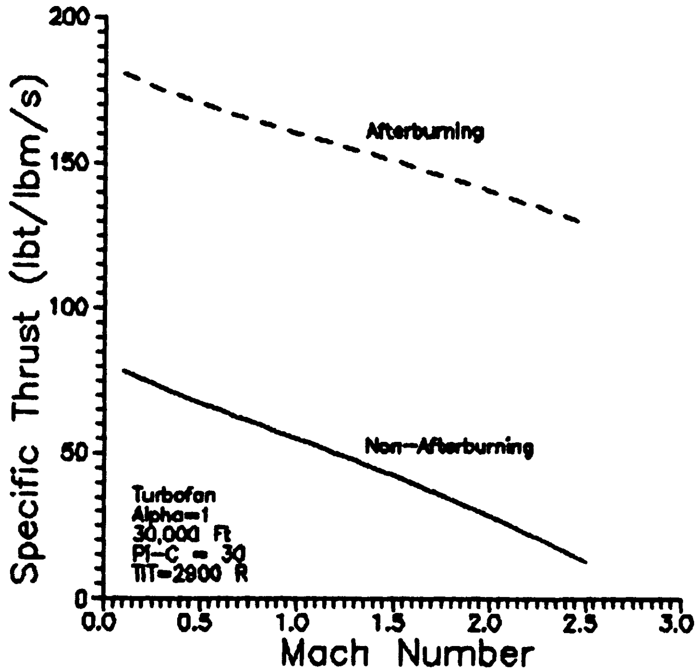

Figure 2-13

Comparison of the Specific Thrust of Afterburning and Non-afterburning Turbofan Engines with a Bypass Ratio of One.

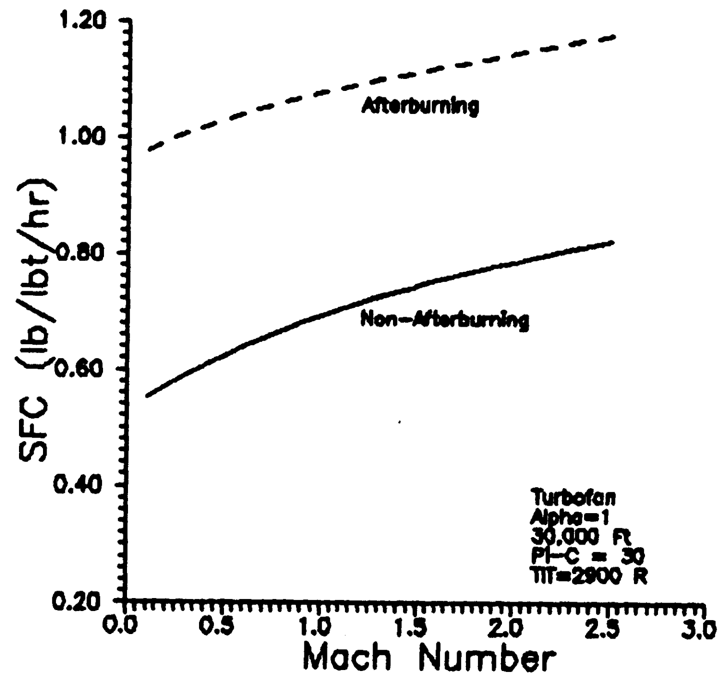

Figure 2-14

Comparison of the Specific Fuel Consumption of Afterburning and Non-afterburning Turbofan Engines with a Bypass Ratio of One.

CHAPTER III

THE MILITARY'S ROLE IN DEVELOPING EARLY COMMERCIAL GAS TURBINE ENGINES

The U.S. aircraft engine industry has been remarkably successful in "spinning off" and adapting military aircraft engine technology for use in the commercial sector. This success has been accomplished by incorporating military aircraft engine technology into commercial engines, improving their specific fuel consumption, thrust, and reliability and providing considerable economic benefit to commercial aviation. Many of the engines currently in service on modern airliners, and most of the engines on earlier commercial aircraft, are derived from military engines. This trend is the historical result of the military's early interest in jet engine technology as a means of enhancing the performance of its fighter and bomber aircraft. Because military interest in jet engines arose well before the commercial interest did, R&D for military aircraft engines paved the way for the development of commercial engines.

This chapter explores the role the military has played in helping to establish and maintain the commercial jet engine industry in the United States. In particular, this chapter documents the transfer of military jet engine technology to the commercial engine industry and attempts to understand the reasons for the successful incorporation of military technology in commercial products. The chapter ends with several conclusions regarding the success of technology transfer between the military and commercial jet engine industries in the U.S. These lessons will later be examined to better understand the potential for continuing the success of the U.S. jet aircraft engine industry.

A. Commercial Jet Engines With Military Antecedents

The extent to which military engine technology has influenced commercial engine development can be appreciated by examining the military content of commercial engines. Many major commercial engines incorporate technology first developed for military engines. In such cases, the degree of similarity between the military and commercial versions varies. In some instances, the commercial engine was a direct commercialization of the military engine. In others, the commercial variant was derived from the core of the military engine, but incorporates a different fan section to create an engine with a different bypass ratio. The following discussion describes the lineage of today's commercial airliner engines in order reveal the degree of military technology contained in these engines. As will be shown, many early military engines and their cores were directly commercialized for airline use.

1. Pratt & Whitney JT3: The First Commercial Airliner Jet Engine

The Pratt & Whitney JT3C engine was the first jet engine used on a commercial airliner. This engine, a straight turbojet, served as the primary powerplant on the Boeing 707 airliner, the first U.S.-manufactured commercial jet airliner and was the first jet engine powerful enough for four to propel such a large aircraft. At sea level, the JT3C generated 12,000 pounds of thrust with a specific fuel consumption of 0.76 lb/lbt/hr[1] (Taylor, 1966, p. 536). While somewhat less fuel efficient than a typical propeller-driven engine of that day (which would have an SFC of approximately 0.42 lb/lbt/hr), the JT3C nevertheless helped lower the direct operating costs (DOC) of airlines. By generating much more thrust than a piston engine, the JT3C could power a larger aircraft to higher velocities than a piston engine, and provide more economical service.

Though a revolutionary engine for the commercial market, the JT3 engine was actually a commercial version of the J57 engine Pratt had developed for the B-52 bomber. Pratt began designing a demonstration version of the J57 with company funds in 1946 in order to make up for their late start in jet engine development (Miller and Sawyers, 1968, p. 162). In 1948 the Air Force funded Pratt & Whitney to continue development of this jet engine for the B-52 bomber. Pratt built the J57 engine to Air Force specifications between 1948 and 1954. Eight of these engines were used to power the B-52.

The J57/JT3 was the first engine to incorporate a dual rotor configuration in which separate turbines were used to power the low-pressure and high-pressure compressor stages or "spools".[2] The earlier single-spool engines could operate efficiently only near their design point. At this point, the rotational speed of the compressor was properly matched to the engine airflow. Under off design

[1]Unless otherwise noted, all values of engine SFC quoted in this document refer to performance under static, sea-level conditions.

[2]The term "spool" is used to refer to the turbine, its associated compressor stage, and the connecting drive shaft.

conditions, the stages of the high pressure compressor were mismatched; the first stages of the compressor had a tendency to stall and the last stages often operated under "turbining" conditions, drawing power from the airflow rather than compressing it. Such an engine has difficulties starting or operating at high velocity (von Ohain, 1987, p. 21). Similarly, if the engine is slowed down or the compressor inlet temperature climbs, the front stages of the compressor supply too much air to the rear stages. The excess air in the rear stages of the compressor initiates a choking action which decreases the airflow through the compressor and increases the chances of engine stall (Treager, 1979, p. 123).

Dual-spool technology solved this problem by using two independently rotating spools. The rates of rotation of the high- and low-pressure spools could then be adjusted separately to operate under a wider range of conditions. In this configuration, the front rotor is designed so that its rate of rotation decreases faster than that of the rear rotor at low speeds to prevent the rear compressor stages from choking.

The JT3 engine in operation on current Boeing 707s and Douglas DC-8s is a modified JT3 engine designated the JT3D. The JT3D incorporates a forward fan section, converting it into a turbofan engine with a bypass ratio of 1.4 (Wilkinson, 1960, p. 89). Such an arrangement offers great advantages in thrust and in specific fuel consumption. The JT3D is capable of generating 18,000 pounds of thrust at take-off with a specific fuel consumption of 0.535 lb/lbt/hr (Treager, 1979, p. 59). At cruise, the SFC of the JT3D increases to 0.80, only slightly higher than that of a piston engine (Miller and Sawyers, 1968, p. 197). This innovation allows the JT3 engine to power larger aircraft, and to do so more efficiently than a straight turbojet design can. Military versions of the J57 (that power the B-52) were also refitted with fans and redesignated the TF-33.

2. Pratt & Whitney JT8:

Pratt & Whitney's success with the J57/JT3 engine led it to introduce a smaller military engine, the J52, in 1960. Like the J57, the J52 was a two-spool turbojet. This engine produces approximately 9,300 pounds of thrust at sea level with a specific fuel consumption of 0.79 (Taylor, 1966, p. 536). It is used to power the Navy's A-6 Intruder and the A-4 Skyhawk.

In 1962, Pratt began offering a commercial version of the J52 to power the mid-sized Boeing 727, 737, and Douglas DC-9 airliners. Over 4,500 JT8A engines were sold in ten years (Trilling, 1983, p. 25). Additional modification of the J52 resulted in the JT8D turbofan engine. This engine was certified for commercial use in 1964 and was designed specifically as a commercial engine. Pratt spent $75 million on its development. The JT8D engine has a bypass ratio of approximately one and generates 14,000 pounds of thrust with a SFC of 0.6 (Taylor, 1966, p. 536). Variants of this engine are still in use on Boeing 727, 737, and McDonnell-Douglas DC- 9 airliners.

3. General Electric CF6: GE's First Commercial High-Bypass Turbofan

General Electric's first commercial high-bypass ratio engine, the CF6 also derives directly from a military engine, in this case, the TF-39. Since its introduction in 1968, the CF6 series of engines has become one of the most successful engine series ever and has formed the core of GE's commercial aircraft engine business. Derivatives of this engine power versions of the Boeing 747 and 767, the DC10, the Airbus 300 and 310. In total, over 27 variants of the engine have been developed.

Although General Electric committed corporate funds to the development of the CF6 in 1967 (Taylor, 1990, p. 733), the technology for the engine derives directly from the T-39 engine GE designed and developed for the Air Force C-5 heavy-lift transport. The CF6 engine shares a common core with the TF-39, meaning that it uses the same compressor, combustor, and turbine sections. The major differences between the CF6 and the TF-39 are in the low-pressure spool, and hence the bypass ratio. The TF-39 has a bypass ratio of eight; the CF6 has a bypass ratio of five. In addition, the TF-39 uses "one and a half" fan stages to properly match its fan pressure ratio to the engine's overall compression ratio. The CF6, on the other hand, uses a just single fan stage despite the fact that it should have a higher fan pressure ratio to properly match the exhaust velocities of the core and bypass airstreams. Additional fan stages would greatly increase the weight of the engine and its noise. While these considerations could be overlooked somewhat in the design of the TF-39, they were significant design constraints in the case of the commercial CF-6 engine (Kerrebrock, 1977, p. 33). Aside from this change, the two engines are highly similar as suggested by Table 2-1 which compares the specifications of the TF-39 and the CF6 engines.

Table 3-1

Comparison of TF-39 and CF6 Specifications

Parameter	TF-39	CF6
Bypass Ratio	8.0	5.9
Compression Ratio	25	28
Turbine Inlet Temp. (°F)	2400	2350
Maximum Thrust (lb)	41,000	39,300
SFC at Takeoff (lb/lbt/hr)	0.315	0.354

[Source: Taylor (1974)]

Development of the TF-39 required GE to solve several technical problems that made later development of the CF6 possible. The first of these was the development of adequate cooling systems. All high-bypass ratio turbofans generate high power levels in the engine core in order to achieve high mass flow rates in the bypass stream. As a result, the large fan associated with the CF6 engine (about 8 feet in diameter) requires extremely high energy densities in the engine core as compared to that required for a turbojet of equivalent thrust. An elaborate cooling system is therefore required for the engine components (especially the turbine) to operate properly in the resulting environment. This cooling system, in turn, adds to the weight of the engine.

In accepting the C-5 engine project, "General Electric was betting that an improved technique for cooling turbine blades would bring to pass what had seemed the impossible: a huge, durable fan engine that could operate safely and efficiently with a very high bypass ratio (as high as eight to one), hence at extreme temperatures" (Newhouse, 1982, p. 113). GE solved the turbine heating problem by introducing air-cooled blades in the TF-39 engine. Air from the core flow was diverted before combustion and pumped into hollow turbine blades, allowing the blades to operate at high temperatures.

The TF-39 and CF6 also required large diameter fan sections to generate the air flow necessary to produce high bypass ratios. These fans, in turn, created additional drag. This drag was originally thought to be so large as to overwhelm any advantage in thrust that could be gained with the larger engine. Furthermore, the large diameter fans required new blade materials that could withstand the large stresses generated by the high tip velocities. GE was able to resolve these difficulties due in part to its experience building large fans for the military's XV-5A "vertifan" vertical takeoff airplane. GE designed an eighty inch fan for the J79 turbojet engine for this application, the efficiency which led GE engineers to speculate that they might perform well on turbofan engines as well (GE, 1979, p. 142). These fans, retained their high efficiency up to high subsonic speeds and could be applied to subsonic aircraft (Miller and Sawyers, 1968, p. 198).

Updated versions of the CF6 power many modern jetliners. CF6-50 is the first major growth version of the CF6 engine[3]. The CF6-50 differs from the original

[3]An earlier growth version, the CF6-45, was also developed, but manufactured only in small numbers.

CF6 in several ways. First, it incorporates a larger fan section to increase its bypass ratio. Two additional "booster" stages are installed behind the single-stage low-pressure compressor to increase the core compression ratio. Also, the CF6-50 operates at a higher turbine inlet temperature (2,425 °F) than the CF6 due to the availability new turbine materials, many of which were developed for military engines (Treager, 1979, p. 42). As a result, the engine generates 52,500 pounds of thrust with a SFC of 0.376 lb/lbt/hr (Taylor, 1990, pp. 733-734).

The CF6-80 represents a more recent modification of the basic CF6 that is designed for even greater thrust. The CF6-80C uses a larger fan section (93 inches) than either the CF6 or the CF6-50. It also replaces the 4-stage low-pressure turbine of earlier models with a 5½ stage turbine to drive the larger fan section. The turbine blades are directionally solidified so they can operate at a higher turbine inlet temperature and with less cooling than the blades on the CF6-50. A new E-series of the CF6-80 is being designed for higher thrust and better fuel efficiency using an even larger fan and higher temperature alloys in the compressors and turbines. The CF6-80 generates up to 64,000 pounds of thrust with a SFC of 0.344 (Taylor, 1990, p. 734). It powers the Boeing 747 and 767, the Airbus 300 and 310, and the MD-11 aircraft (*Aviation Week*, March 18, 1991, p. 133)

4. Pratt & Whitney JT9: The First Commercial High-Bypass Turbofan

Despite the experience General Electric gained in the development of high bypass turbofans during the TF-39 program, the first commercial high-bypass turbofan, the JT9D, was actually developed by Pratt & Whitney. This engine, with a sea-level static thrust of approximately 45,000 pounds and a SFC of 0.346 (Taylor, 1990, pp. 741-742), powered the first Boeing 747s and later powered the 767 and DC-10. Several modified versions of the JT9D have since been developed and sold to Boeing, McDonnell-Douglas, and Airbus.

The JT9D derived from Pratt's experience with USAF heavy freighter propulsion in 1961-1963 (Taylor, 1972, p. 783) and Pratt's entry in the TF-39 competition. Though they lost the competition (primarily because they bid an engine with a lower bypass ratio than GE), Pratt had gained considerable experience in the design of high bypass turbofan engines. Throughout the bidding process, they were forced to confront the issues of cooling and fan construction that were necessary for developing such engines.

The JT9D engine developed for the original 747 was similar to the engine Pratt & Whitney had designed for the C-5A. However, to meet the thrust and fuel consumption requirements of the 747, Pratt increased the bypass ratio of the engine from 3.4 to 5.0. The first JT9D engines delivered to Boeing had a maximum thrust of 43,500 pounds and a SFC of 0.346. They also incorporated a number of technological improvements over previous engines. The JT9D used an improved fan design that could efficiently maintain the desired fan pressure ratio with a single stage and no inlet guide vanes. The improved compressor allowed an overall compression ratio of 24:1 with 15 stages as compared to the 14:1 compression ratio achieved on the JT3D with 16 stages. Improvements in materials and cooling allowed the turbine inlet temperature to be increased to 2270° F.

Several upgraded models of the JT9D have been developed since then. These incorporate new turbine blade materials to increase the operating temperature of the engine and larger fan sections. Take-off thrust for these engines is between 43,000 and 56,000 pounds. SFCs range between 0.34 and 0.37 lb/lbt/hr (Taylor, 1990, pp 741-742).

5. CFM International CFM-56

CFM International's CFM-56 engine also derives from military technology. This high-bypass turbofan engine generates between 22,000 and 31,000 pounds of thrust with a SFC of 0.33 to 0.36 lb/lbt/hr (Taylor, 1990, pp. 699-700). The CFM-56 is now offered on several medium sized aircraft including the 737-300, KC-135, and A320.

The CFM-56 is produced by CFM International, a joint venture formed by General Electric and SNECMA, a French aircraft engine company. These partners share both the development and production of the engine and hence share profits from its sale. GE developed core and controls; SNECMA developed the low pressure system including the fan, thrust reverser, and gearbox. The two companies shared only interface requirements for their parts of the engine so they would not have to exchange technical details of their components (MIT, 1989, p. 76).

Such an arrangement was necessary to protect the technology contained in the core of the engine. The core derives from the F101 engine GE developed for the B-1A program. During the 1960s, the Department of Defense (DoD) funded the development of an engine for the Advanced Strategic Manned Bomber which later resulted in the B-1A bomber program. GE designed a new core for this engine to meet its special operational requirements. The resulting F101 engine was designed as a 30,000 pound thrust class engine with a bypass ratio of 2.2 and an afterburner for supersonic flight capability. The engine was selected for B-1A in 1970.

After cancellation of B-1 in the early 1970s, GE and SNECMA teamed to produce an engine which used the F101 core. The resulting CFM-56 engine uses the original F101 core, but with a new low-pressure fan spool that increases the engine's bypass ratio to 6.0. This change also lowered the SFC of the engine to an acceptable level for commercial operations, between 0.32 and 0.39 lb/lbt/hr. SFC values for the F101 engine are currently classified under security restrictions.

B. The Development of the Gas Turbine Engine: An Historical Review

As the above discussion demonstrates, the military has played an important role in developing technology for use in commercial engine applications. The JT3D, JT8D, JT9D, CF6, and CFM-56 engines are all based around technology developed for military engines. The reasons for the commercial engine industry's heavy reliance upon the military can best be understood in a historical context. As will be shown below, the military became interested in the development of jet engines well before the commercial airliners and thus gained a head start in the development of such engines. Primarily, the military was interested in increasing the thrust available from a given power-plant so that it could increase the speed and altitude at which its aircraft flew. The commonality between the technology required to meet military and commercial interests at that time enhanced the flow of technology between these two sectors of the jet engine industry.

1. The First Gas Turbine Engine

Development of jet engines was spurred primarily by the military's desire for higher thrust engines. Despite the development of the turbosupercharger, piston engines were limited in several ways. First, these engines could not propel aircraft to high subsonic velocities. Such flight required engines with a much higher thrust-to-weight ratio than the piston engine could achieve. Secondly, as flight speeds approach the speed of sound, the efficiency of propellers decreases and the level of noise they produce increases dramatically (von Ohain, 1987, p. 14). Finally, advances in turbosupercharger technology had resulted in engines that were mechanically complicated and unwieldy. The additional weight of large superchargers needed for high-altitude flight began to increase the weight of the overall engine to unacceptable levels.

At this time, engineers in the Army Air Corps and at General Electric became aware of advances in a new engine technology in Great Britain, the jet engine, for which Frank Whittle, an officer in the Royal Air Force received a British patent in 1930. U.S. interest in the jet engine was spurred by General H. H. Arnold, the head of the U.S. Army Air Corps, who wrote to Vannevar Bush, the Chairman of the National Advisory Committee for Aeronautics and of the National Defense Research Committee, and requested the formation of a committee to pursue the development of the jet engine in the United States. General Arnold specifically requested that leading aircraft engine manufacturers be excluded from the program because he thought their experience with piston engine might make them resistant to the new gas turbine technology and because the piston engine developers were heavily involved in producing engines for the wartime buildup (GE, 1979, p. 41). Three companies were granted contracts to develop jet engines: General Electric, Allis Chalmers, and Westinghouse. All three had previously been awarded contracts to study marine gas turbines and seemed a logical choice for developing aircraft gas turbine engines. Allis Chalmers and Westinghouse received contracts from the Navy; GE from the Army. Neither Pratt & Whitney or Wright, the primary suppliers of piston engines to the military and commercial markets, were included in the contest.

GE received additional assistance from the military in developing their jet engine. After General Arnold witnessed the flight of a British jet-powered aircraft and became more convinced of its utility to the U.S. military effort, he negotiated a deal with the British Air Commission whereby GE was given access to the design details of the engine. Eventually, an actual Whittle engine was shipped to GE for inspection (GE, 1979, p. 44). With this assistance, GE successfully demonstrated an operational jet engine, the GE I-A, in April 1942. It generated 1,250 pounds of thrust. The first test flight, aboard a P-59 aircraft occurred just five months later.

Subsequent models of the GE I, designed to power other military aircraft, increased its power rating to 2,000 pounds of thrust.

Following the development of the GE I engine, the military remained the primary benefactor of engine development. As during World War II, its main emphasis was placed upon increasing the thrust of jet engines so that they could power aircraft to higher altitudes and velocities. By 1947, GE, with backing from the Air Force, had designed the J-33 engine to power the F-80 fighter aircraft. This engine provided 4,000 pounds of thrust and could propel the F-80 to speeds of over 620 miles per hour.

Pratt & Whitney, though excluded from the initial research programs managed to keep abreast of technological developments through the investment of corporate funds. In 1943, Pratt & Whitney invested its own money in a program to develop a "free piston" jet engine which would drive a propeller through a gear reduction box. The project did not result in the development of a complete engine, but along with a subcontract Pratt had won from Westinghouse, this project enabled the company to become knowledgeable of the new technology. In 1948, Pratt purchased the licensing agreement from Rolls Royce allowing them to manufacture the Rolls Royce Nene engine in the U.S. (Trilling, 1983, pp. 22-23).

2. Improved Performance with Axial Flow Engines:

These early jet engines were "centrifugal flow" engines. They compressed ambient air by driving the airflow radially from the center of the engine. Such compression was highly efficient, but limited in magnitude. In order to increase compression ratios, the diameter of the engine had to be continually expanded, increasing the weight of the engine and the drag it produced. Above compression ratios of six to eight, the efficiency of the centrifugal flow compressor decrease rapidly because of the high impeller tip speeds required and because of shock wave formation. (Treager, 1979, p. 117). Thus, centrifugal flow engines were limited to thrusts of approximately 5000 to 7000 pounds and SFCs of approximately 1.0 to 1.25 (Trilling, 1983, p. 23).

Axial flow engines could overcome some of these limitations. In an axial flow engine, the ambient air is compressed as it flows axially through the engine. Successive compressor stages, compress the air sequentially as it travels through the engine. Using such a technique, high compression ratios can be achieved with a smaller frontal area than a centrifugal compressor. The higher compression ratio results in engines of inherently higher thrust. Throughout the 1940s, the military sponsored development of axial as well as centrifugal engines. The first U.S. axial flow engine, the GE J35 was flight tested in 1946 and provided performance comparable to that of the centrifugal J33 (GE, 1979, p. 56). Additional development produced the GE J47 engine, an axial flow turbojet with a maximum thrust of 5,500 pounds.

Pratt & Whitney also entered the jet engine market at this time. Previously, the Air Force had worked almost exclusively with GE to develop jet engines while Pratt continued to concentrate its efforts on producing piston engines for commercial use. However, in 1948 Pratt negotiated a contract with the Air Force to develop the J57 turbojet engine for the B-52. With this contract, Pratt hoped to establish itself as a jet engine producer. By granting Pratt & Whitney this contract, the Air Force not only hoped to develop a larger turbojet engine, but also hoped to expand their source for jet engines.

Pratt developed the J57 for military applications, but soon after offered a commercialized version of the engine, the JT3. Unlike earlier commercial jet engines such as the GE J47, the JT3 sold well. Boeing, who had gained experience with the J57 engine on its B-52 bomber, developed the 707 airliner to use the JT3. McDonnell-Douglas soon followed suit with the DC-8 aircraft. The commercial success of the 707 and the DC-8 enabled Pratt & Whitney to retain its position as the leading supplier of engines to the commercial market as neither GE nor Rolls-Royce could offer a comparable engine (Trilling, 1983, p. 24) In total, over 25,000 J57 and JT3 engines were sold to military and commercial customers by 1972.

The JT3 engine succeeded commercially for a combination of economic and technological reasons. Previous jet engines did not appeal to commercial airlines because the engines did not appear to improve their competitive stature. Early jet engines were limited in thrust and had SFCs higher than the pistons engines of that time[4] Thus, they were more expensive to operate. Jet-engine aircraft became

[4]A typical piston engine during the mid-1940s had a specific fuel consumption of approximately 0.42 lb/lb/hr compared to about 1.0 for a comparable jet engine.

economical only when they could fly at speeds greater than 450 miles per hour (Miller and Sawyers, 1968, p. 153) and could be made large enough to power a large aircraft that carried many passengers. The JT3 provided this capability. This engine, with a maximum thrust rating of 11,200 was the first engine powerful enough that four could power a large jetliner such as the Boeing 707. Though its SFC was still considerably higher than that of a piston engine, the JT3 could propel an airliner to high enough speeds to make the flight economical. High-speed flight appealed to airline passengers and helped to increase the market for airline operations (Miller and Sawyers, 1968, p. 177).

3. Turbofan Engines:

Although Pratt and GE continued to produce improved turbojet engines such as the Pratt & Whitney J75 and GE J79 over the next decade, the next major innovation in the engine industry did not occur until the late 1950s when GE produced the first U.S. turbofan engine[5]. The operating principle of the turbofan had actually been worked out by Whittle years earlier, but not until the airlines desired the enhanced performance of the turbofan did the engine become a reality (GE, 1979, p. 121). The turbofan consists of a turbojet engine modified by placing a fan in a cylindrical duct surrounding the engine to accelerate a stream of air around the core of the engine. Such engines could generate 15,000 to 20,000 pounds of thrust with SFCs on the order of 0.50 to 0.65 lb/lbt/hr.

GE developed the first turbofan engine in the U.S. by adding a fan to the

[5]Rolls-Royce had also been experimenting with the turbofan concept at about the same time.

rear of its CJ805 engine, a commercialized version of the J79. GE engineers believed that such a modification would improve the takeoff thrust of the engine by 40% and the SFC of the engine by 15% (GE, 1979, p. 121). The new aft-fan engine was designated the CJ805-23 and was designed for the Convair 990 aircraft, a faster version of the Convair 880. Though the Convair 990 failed technologically and financially[6], American Airlines became interested in replacing the JT3 engines on its 707s with the CJ805-23 in order to increase their range and lower their fuel consumption. Pratt & Whitney, which had previously opposed the turbofan concept, agreed to equip its JT3 engines with a fan. American's 707s were reequipped with the new JT3D engines. These engines could generate 17,000 pounds of thrust with a SFC of 0.52 lb/lbt/hr.

Although the Air Force eventually refitted its B-52 bombers with the a fan version of the J57 (the TF-33), the development of the turbofan rested solely upon commercial considerations. The military provided the basic engine core from which the turbofan could be created, but the military did not provide the impetus for such innovation.

4. High-Bypass Turbofan Engines:

The next development in engine technology, high-bypass ratio turbofans, was strongly affected by military requirements and funding. In 1962, the Air Force announced a requirement for a large, wide-body transport that would require 200,000 pounds of total thrust. Pratt & Whitney and GE competed for the engine

[6]The 990 aircraft lost $425 million for Convair in 1960-61.

portion of the work. Because the thrust requirements for the C-5A were double the capability of any existing engine, both competitors were forced to examine the potential for high-bypass turbofan engines. As discussed previously, the design of such engines required advances in fan aerodynamics, turbine blade cooling, and turbine inlet temperatures. In order to generate sufficient thrust from a high bypass turbofan, turbine inlet temperatures had to be increased from 2100°F to nearly 2500°F. GE won the competition by proposing the TF-39 engine with a bypass ratio of eight as compared to 3.4 for Pratt's entry. The contract was worth over $495 million to GE at that time (GE, 1979, p. 151).

Soon after the C-5A competition, Juan Trippe, the President of Pan American Airlines began negotiating with Boeing to build the 747. Boeing had recently lost its bid to build the C-5A airframe, but as a result of that experience and its earlier work on Air Force bombers, had the capability to build a large aircraft. Boeing and Pan Am approached GE about building the engines for this aircraft, but GE was "too busy" with the C-5 to build a commercial engine. Moreover, GE management was reluctant to start on a large commercial fan engine venture until the Air Force had spent more money on the military prototype. They wanted the military to absorb the cost of development. (Newhouse, 1982, pp. 117-118)

In April 1966, Pratt & Whitney was selected to take on the project primarily because of their experience with the C-5A. Rolls-Royce had also entered a bid for the 747 engine, but had only a paper design. They had never built, nor attempted to design, an engine of the scale required for the 747. Boeing and Pan Am recognized that Pratt had extensively researched the problems associated with high-bypass turbofans on the C-5A proposal and granted them a contract for the 747 engine.

Pratt accepted this contract despite the uncertainty associated with the new technology so they could maintain their position as the leading supplier of commercial engines. They feared that allowing GE or Rolls-Royce to take on the project would jeopardize their market position. At that time Pratt held almost 90% of the commercial market and made most of their sales to that market (Newhouse, 1982, p. 120). The engine they produced for the 747, the JT9D, has since become the mainstay of Pratt's commercial operations.

5. Subsequent Developments:

Since the introduction of the high bypass ratio turbofan in 1968, commercial interests have focused on modifications to this basic engine type. Between 1968 and 1991, GE introduced no entirely new commercial engine types; rather, it produced upgraded versions of the CF6. Pratt, too, continued to modify the JT8D and JT9D. Only recently has Pratt developed new commercial engine types.

Pratt's two newest high bypass turbofans are the PW2000 and PW4000 series engines. The PW200 produces approximately 40,000 pounds of thrust at sea-level with a SFC of 0.33 (*Aviation Week*, 1991b, p. 135). At 35,000 feet and Mach 0.8, the SFC of the engine is 0.563. The first version of the PW2000 was designed for the Boeing 757-200 aircraft; a modified version will be used on the military's C-17 transport. The PW4000 is a higher thrust turbofan. Present versions generate 52,000 to 60,000 pounds of thrust with a SFC between 0.311 and 0.330. They are used on Boeing 747, 757, 767 and Airbus 300, 310, and 330 aircraft. Both of these engines incorporate increased compression ratios, single-crystal turbine blades, and full-authority digital electronic controllers (FADEC) to control fuel flow to the engine. Much of this technology derives from Pratt & Whitney's centralized Engineering Division which develops basic technology for both commercial and military applications. Thus, the degree to which these two engine programs have benefitted from military research is difficult to determine.

Military interest, on the other hand, has centered upon low-bypass ratio engines to power fighter aircraft such as the F-14, F-15, F-16, and F-18 and the B-1 bomber. Such engines provide sufficient thrust to power these aircraft while providing a small cross-sectional area. Thus, they produce less aerodynamic drag than high-bypass ratio engines and can be more easily integrated within the airframe. Fighter aircraft use the PW F100 series, GE F110 series and GE F404 series engines. The B-1B uses the GE F101. The B-2 uses a modified F110 engine designated the F118. Of these, only the F101 has been used as the core of a commercial engine. Nevertheless, advances in materials for increased turbine inlet temperatures have been transferred to new and older modified commercial engines.

C. Conclusions:

As the above discussion demonstrates, the military has played a significant role in supplying technology to the commercial aircraft engine industry. The military has developed technology with potential commercial application and that technology has been successfully transferred to the commercial manufacturers. The success of such technology transfers appears to be the result of a fortuitous series of interactions between military and commercial interests and between the firms engaged in engine development. Despite many apparent obstacles to technology transfer, the technology developed for military applications was effectively utilized in the commercial sector, bringing with it tremendous benefits to the U.S. economy.

1. Apparent Barricades to Technology Transfer:

On the surface, the prospect for technology transfer from early military engine programs to the commercial sector appears bleak in retrospect. Jet engine technology was "developed to military specifications, for military needs with military funds, by a set of producers new to the aircraft engine field and brought in by the military" (Trilling, 1983, p. 28). Commercial interests, which were widely divergent from military interests, were not represented in much of the early military development of the jet engine.

In developing the jet engine, the military intentionally prevented manufacturers of commercial engines, namely Pratt & Whitney and Wright Aeronautics, from entering the competition. The military believed that because of their reliance on piston engine technology, these companies would resist the development of a new technology that might prove to outdate their technology base (GE, 1970, p. 40). The military instead contracted with GE to produce the first jet engine. GE had extensive experience with steam turbine engines and had worked previously with the military on turbosuperchargers to increase the performance of piston engines at high altitude. As GE's engine operations had no relationship with the commercial aircraft market until it developed the CJ805-23 engine in the early 1960s, their selection to develop the jet engine temporarily precluded the transfer of jet engine technology to the commercial sector. Moreover, it eliminated commercial influences from the design of early jet engines. Not until Pratt & Whitney entered the jet engine market in 1952 with the JT3 engine did a commercially-oriented company enter the jet engine competition.

Furthermore, military and commercial interests in jet engine technology were based on different operational requirements. The military interest was based upon improving the speed and altitude capability of its aircraft. Hence the military emphasized the development of engines with greater thrust--or more correctly greater specific thrust. The development of the jet engine as a replacement for the piston engine itself represented an attempt to surpass the limits on aviation imposed by piston engine technology. Further innovation repeated this same theme. The use of axial compressor flow (as opposed to centrifugal flow) allowed increases in compression ratio, and hence thrust, without enlarging the diameter of the engine and causing it to become heavier and less aerodynamic. The development of the high bypass ratio turbofan was also an attempt to increase engine thrust.

Commercial airlines, on the other hand, have sought to develop new engines in order to decrease direct operating costs. This requirement at first emphasized the development of higher thrust engines, but has since shifted commercial interests toward lowering SFC. The airlines' original resistance to jet engine technology was based upon the fact that early jet engines provided no economic benefit to the airlines. Their subsequent adoption of jet engine technology occurred only when the technology had matured sufficiently to allow more economic operation than did piston engines. Development of the turbofan engine was also a direct result of commercial pressure for greater engine efficiency. As mentioned previously, military requirements had no influence on the development of the first turbofan engine. This trend has continued through the present as evidenced by the use of high bypass turbofans in commercial airlines which can also be seen as an attempt to decrease direct operating costs. High bypass turbofans produce sufficient thrust to power larger airliners and do so with a considerably lower SFC than other types of engines offer.

2. Reasons for the Successful Technology Transfer:

The success of the military in supplying technology for the commercial industry in many ways results from the fact that similar technology addressed the requirements of both sectors of the industry. Although many operational requirements for the two sectors were vastly different, the technological basis for meeting these requirements was similar. Whereas the increased thrust provided by the first turbojet engines translated into improved aircraft speed and altitude for military aircraft, it translated into improved operating efficiency for commercial aircraft. High bypass turbofan engines, while providing the large amounts of thrust required to power the oversized C-5 aircraft, simultaneously provided airliners with a fuel efficient powerplant for large, economical aircraft.

In addition, the jet engine industry developed a structure conducive to successful technology transfer. Jet engine technology quickly became concentrated in the hands of two major contenders that developed both military and commercial operations. Thus, engine R&D is highly centralized, eliminating some of the barriers to technology transfer (although security restrictions are still an impediment). GE, though initially brought into the engine industry as a military supplier of engines, developed a commercial practice with the CJ805-23 turbofan. Conversely, Pratt, which had been heavily involved the commercial market for piston engines, developed ties to the military in order to take advantage of military technology and funding. Both major contenders in the jet engine business are also part of larger corporations with substantial financial resources. Thus, both were able to pursue long-term corporate strategies that were not solely dependent on military sales of engine. The resources of the larger conglomerates enabled these companies to dominate other, smaller firms that had been active in piston engine production (Trilling, 1983, p. 28).

3. The Commercial Benefit from Technology Transfer:

As a result of this fortuitous combination of technological and organizational factors, the U.S. commercial engine industry has benefitted greatly from military investments in jet engine technology. As a result of military investment in jet engine R&D, the commercial industry has gained technology with greatly reduced costs and risks. The military not only developed and tested new engine technologies that had application to commercial needs, but it developed engine cores that have become the basis of many commercial engines. The significance of this military funding is summarized by Miller and Sawyers as follows:

> The most unequivocal gift that governments made to the aircraft industry was the jet engine itself: it is unlikely that its development would have been carried through without government aid, and the first jet airliners were able to use engines almost identical with those developed for military aircraft (Miller and Sawyers, 1968, p. 156)

The military has effectively underwritten the cost of developing military and many commercial engines. Such funding is particularly important in the jet engine industry because new engines are expensive to develop. Recent figures estimate that the development of a new engine cost approximately one billion dollars and takes five years (Newhouse, 1982, p. 161). Manufacturers can not expect to earn a profit on their investment for approximately fifteen years when the profit from sales finally surpasses the cost of R&D (MIT, 1989, p.79). Thus, without an assured market for a new engine, companies are often unwilling to make large investments in a risky technology. The military, provides industry with an assured market. Moreover, the military will pay the full cost of developing and producing a new engine.

In addition, the military is willing to assume greater risks than commercial industries in developing new technology. Unlike the commercial airlines which frequently ask for performance guarantees on new engines, the military accepts the risk inherent in developing new engine technologies. The rapid progress made by engine manufacturers in increasing the thrust and efficiency of jet engines was influenced by the large investments the military made in their development, which reflected the desire of the Air Force to have better engines for its aircraft. Without the pressure and financial support of the military, manufacturers would not have accepted the risks inherent in many of the technological advances they made with engines such as the J57 and the TF-39 (Miller and Sawyers, 1968, p. 163).

The military's willingness to accept risk enabled the engine manufacturers to demonstrate many technologies applicable to commercial industry. Both the jet engine technology and the high-bypass turbofan engine technology were proven in military programs. Though the risks associated with these programs were large, engine manufacturers were able to recoup their investments in R&D and thus willing to accept the projects.

The military has also developed engine cores that later served as commercial engine cores. In fact, few new cores have been developed explicitly for commercial industry. GE has maintained its position as the low-cost supplier of engines by basing its CF6 series engines upon the TF-39 core. Twenty-seven variants of the CF6 have since been developed for commercial application. While many of these incorporate incremental improvements in materials and cooling or minor changes in compressors and turbines, no completely new core has been developed for these engines. Similarly, CFM International's family of CFM-56 engines derive from the F101 core.

Because technology transfer from the military sector successfully introduces performance innovations to the commercial sector, commercial innovation has concentrated on sector-specific issues such as noise abatement, safety, and fuel consumption. While important to the viability of the commercial sector, these areas of innovation have less significance in the military setting in which performance takes priority over fuel efficiency, excess noise can be tolerated at remote bases, and passengers other than the pilot and copilot are not carried on military aircraft.

Thus, the transfer of technology from military to commercial industry appears to have played a significant role in establishing and maintaining the commercial engine industry. The military has both demonstrated technologies and developed engine cores that were applicable to commercial interests. The commercial industry has thus been able to dedicate more of its resources toward solving problems specific to commercial application. The reason for the successful transfer of this technology appears to have been the ability of similar technologies to simultaneously address military and commercial needs. While military and commercial interests in jet engine technology derive from different requirements, the same technology has been able to serve both these interests.

The future success of technology transfer will also hinge on the ability of military engine technology to satisfy commercial requirements. As the structure of the industry has remained highly stable over the past several years, the means for transferring technology from military to commercial programs still exists. What is needed is military technology with commercial applicability. The next two chapters of this thesis will examine military and commercial requirements for aircraft in order to estimate the degree of similarity between future commercial and military engines. This information will serve as a basis for assessing the nature of future technology transfer from military engine programs to commercial programs.

CHAPTER IV

FUTURE AIRCRAFT AND ENGINE REQUIREMENTS

The degree to which future military R&D in jet engine technology will apply to commercial engine development will be strongly influenced by the nature of the requirements established for future military and commercial aircraft. Though these requirements need not be identical, they must have similar technological bases in order to foster continued technology transfer. As demonstrated in Chapter III, the goals of early military and commercial aircraft development were different, but technology transfer succeeded because the same engine technologies served both military and commercial interests. In order to estimate the potential that future military engine technologies hold for commercial application, one should therefore examine the requirements that will be placed on new engines. This process can best be achieved by examining military and commercial aircraft and determining the types of engines likely to power these aircraft.

This chapter examines likely requirements for future military and commercial engines by examining the technological advances required to improve the performance of military and commercial aircraft. This chapter does not attempt to generate an exhaustive list of current military and commercial R&D programs, rather it attempts to identify general directions in which aeronautical research will progress. Commercial and military customers have different measures of aircraft performance. The commercial airlines evaluate future performance in economic terms such as direct operating costs and profitability. The military evaluates performance in terms of an aircraft's ability to meet demanding mission requirements such as speed, maneuverability, range, and payload. Whereas in the past, these two means of evaluation often resulted in similar engine requirements, application of these same principles may in the future dictate a need to develop different types technologies and hence different engines.

A. Basic Aerodynamics:

Much of the following discussion of engine requirements will be based upon simple aerodynamic analysis of military and commercial engines. Because of the technical nature of this analysis, a brief introduction to aerodynamics seems appropriate at this point. Several references provide complete presentations of this material (Nicolai, 1975; Raymer, 1989; and Shevell, 1989). The discussion herein will introduce only basic concepts of lift and drag in order to elucidate the subsequent discussion.

1. Forces Acting Upon an Aircraft:

A non-accelerating aircraft in flight is subject to four primary forces. As shown in Figure 4-1 these forces are weight, thrust, lift, and drag. Weight results from the gravitational attraction between the earth and the aircraft and is directed radially toward the center of the earth, or downward as shown in the figure. Thrust is the force generated by the engine that propels the aircraft in its direction of motion. These two forces are counteracted by the forces of lift and drag, which are determined by the shape and velocity of the aircraft. Lift is a force generated primarily by the wing section of an aircraft and directed perpendicular to the aircraft's direction of motion. Drag is a resistive force caused by the motion of the aircraft through the air. It acts in a direction that is opposite to the aircraft's direction of motion.

During cruise, aircraft typically operate at a constant altitude[1] and velocity. This condition requires that no net forces be acting on the aircraft, or that the weight of the aircraft be balanced by the lift force, and the drag on the aircraft be equal to the thrust provided by the engine. In mathematical terms, this equilibrium condition can be expressed as shown below:

$$L = W \tag{4-1}$$

$$D = T \tag{4-2}$$

In this nomenclature, L designates the lift force; W, the weight of the aircraft; D, the drag on the aircraft; and T, the engine thrust.

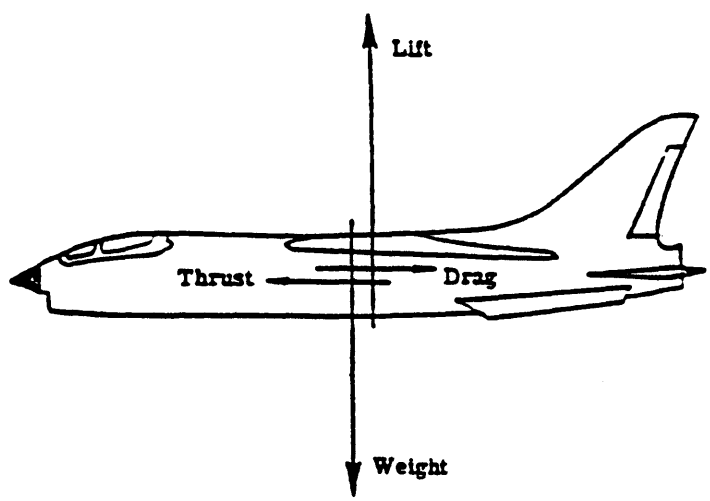

Figure 4-1. Forces Acting Upon an Aircraft in Level Flight [From Talay, 1975, p. 23].

[1]Altitude may vary as the aircraft burns fuel and becomes lighter. This effect will be discussed later in the text.

The forces of weight and thrust in these equations are familiar from everyday experience. The aerodynamic forces of lift and drag, however, are less intuitive and require further elaboration.

2. Lift:

Lift is a force generated by the passage of air over a wing or an airfoil. It is dictated by the application of Bernoulli's principle to the flow of air over the wing surface. According to Bernoulli's equation, the total pressure along a subsonic streamline is constant. Since total pressure is the sum of the static and dynamic pressures, Bernoulli's equation can be written as:

$$p_t = p_s + q \tag{4-3}$$

where p_t is the total pressure of the airstream, p_s is the static pressure of the airstream, and q is the dynamic pressure of the airstream defined by the relation $q = \frac{1}{2}\mu v^2$. In this relation, μ is the air density, and v is the velocity of the airstream. Wings are shaped so that air passing over the top of the wing reaches a higher local velocity than the air passing below the wing. Hence, the air above the wing has a higher dynamic pressure than the air below the wing. According to Bernoulli's equation, the air passing over the wing must therefore have a lower static pressure than the airstream passing below the wing[2]. The difference in pressure above and below the wing generates a force directed perpendicular to the wing section. The component of this force perpendicular to the aircraft's direction of motion is called the lift force.

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[2]Assuming that downstream from the wing, the air has a uniform static pressure and free-stream velocity.

Lift is usually expressed in terms of a dimensionless coefficient, C_L, which relates the overall lift force to the area of the aircraft wing, S_{ref}, and the dynamic pressure of the airstream, q. In this form, the equation for lift becomes:

$$L = qS_{ref}C_L \tag{4-4}$$

The lift coefficient, C_L, varies with the angle at which the incident airstream strikes the wing. This angle is referred to as the "angle-of-attack" and is denoted by the greek letter α. More precisely, angle-of-attack is defined as the angle between the aircraft's direction of motion and its pitch attitude. The variation of C_L with angle of attack is typically measured in wind tunnel tests for a particular wing section. Figure 4-2 shows the result of such measurements on the Boeing 767-300 commercial transport (Roskam, 1987, p. 367). In this graph, the normalized coefficient of lift is plotted as a function of angle-of-attack. As shown, coefficient of lift increases linearly with angle-of-attack until an angle of approximately 15 degrees. At this point, the lift generated by the wing begins to fall off rapidly because the airflow over the top of the wing begins to separate from the wing surface. This condition is referred to as "stall" and establishes the maximum angle-of-attack for operation of most aircraft. At higher angles of attack, alternative means of providing lift (such as with directed thrust) must be utilized to keep the aircraft aloft.

The intersection of the C_L curve with the y-axis determines the minimum coefficient of lift for the wing in level flight. In the case of the 767, C_{Lmin} equals approximately 0.25. For a perfectly symmetrical wing, the minimum coefficient of

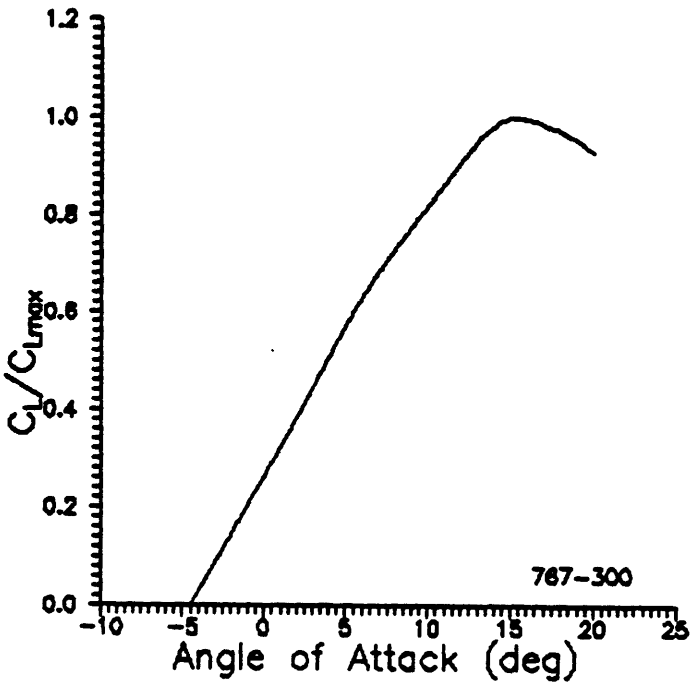

Figure 4-2. ***Variation in Coefficient of Lift with Angle-of-Attack for the Boeing 767-200 [From Roskam 1987, p. 367].***

lift (the value of C_L at $\alpha=0$), is zero. However, if the wing is "cambered", so that the centerline connecting the leading and trailing edges is arched, lift can be produced at zero angle of attack, allowing the aircraft to remain in flight in a horizontal position.

In analyzing aircraft aerodynamics, wing coefficients of lift do not need to be generated empirically. Rather, one can make use of the fact that in level flight, the total lift generated by the aircraft must equal the weight of the aircraft. Thus, equations 4-4 and 4-1 can be equated to produce the following expression for C_L:

$$C_L = W/(qS_{ref}) \qquad (4\text{-}5)$$

By determining the correct value of q for the aircraft's altitude and velocity, the value of C_L required for steady flight can be computed.

3. Drag:

Drag on an airplane refers to all those factors that retard the progress of the aircraft through the air. As with lift, drag is typically specified in terms of a drag coefficient, C_D, which scales the drag to the wing reference area and the dynamic pressure of the airstream. The expression for drag is therefore of the form:

$$D = qS_{ref}C_D \tag{4-6}$$

where q and S_{ref} are as defined previously. In subsonic flight, the coefficient of drag is composed of two parts, a parasite drag component and an induced drag component. In transonic and supersonic flight, an additional component, wave drag must also be considered. Parasite drag, induced drag, and wave drag are calculated or measured separately, but, the contribution of wave drag is often included in the parasite drag coefficient. Thus the expression for the total coefficient of drag is usually expressed as:

$$C_D = C_{D0} + C_{Di} \tag{4-7}$$

where C_{D0} refers to parasite drag and C_{Di} refers to induced drag.

Parasite Drag: The term parasite drag or "zero-lift" drag refers to the drag caused by skin friction and viscous forces as the aircraft passes through the air. The coefficient of parasite drag remains nearly constant regardless of aircraft speed or operating conditions. It is a function primarily of the shaping of the aircraft, its surface roughness, and the total "wetted area" of the aircraft, that is, the total surface area of the aircraft exposed to the airstream. Because parasite drag is nearly constant, the coefficient of parasite drag is designated C_{D0}. This coefficient is typically measured in flight tests or wind tunnel tests. Nevertheless, several analytical techniques for approximating C_{D0} from physical characteristics of the airframe have been developed. Both Roskam (1987) and Raymer (1989) present such techniques.

Induced Drag: Induced drag varies with the lift generated by the wing. As the angle-of-attack of a wing is increased, a force is generated normal to the wing surface that is proportional to the pressure differential between the upper and lower surfaces of the wing. The component of this force perpendicular to the aircraft's direction of motion is referred to as lift; the component of the force opposite to the direction of motion is called induced drag. Induced drag is proportional to the square of the lift coefficient. Empirical tests suggest that this relationship can be modelled by the relation:

$$C_{Li} = K\, C_L^2 \tag{4-8}$$

The proportionality constant, K, can be estimated using several techniques. Typically, K takes the form:

$$K = 1/(\pi\, A\, e) \tag{4-9}$$

In this expression, the term A refers to the "aspect ratio" of the wing section which measures the ratio of a wing's length to its width. In the case of tapered wings, the aspect ratio can be computed by dividing the total wing area, S_{ref}, by the square of the wingspan, *b*. Hence,

$$A = S_{ref} / b^2 \tag{4-10}$$

The symbol, e, in equation 4-8 is termed the "Oswald span efficiency factor". It is a comparative measure of the efficiency of a given wing to the efficiency of an elliptically-shaped wing. Values of e typically fall between 0.70 and 0.85 for subsonic aircraft, but decrease to 0.30 or less during supersonic flight. Raymer (1989) presents an expression for determining the Oswald span efficiency for a wing whose leading edge is swept back at an angle Γ_{LE}:

$$e = 4.61\ (1-.045\ A^{0.68})(\cos\Gamma_{LE})^{0.15} - 3.1 \tag{4-11}$$

With this expression, the coefficient of induced drag can be estimated from a simple sketch of the aircraft. The overall coefficient of drag, C_L, for the aircraft can then be written:

$$C_L = C_{D0} + C_L^2/(\pi\ A\ e) \tag{4-12}$$

<u>Supersonic and Transonic Wave Drag:</u> Additional sources of drag must be considered when calculating the drag on an aircraft operating at transonic (Mach numbers 0.8 to 1.2) or supersonic velocities. Aircraft operating at these speeds are subject to increased wave drag caused by the formation of shock waves along the aircraft. Wave drag in supersonic flight is often greater than the sum of all other drag effects. It is a direct result of the way in which an aircraft's volume is distributed. Techniques such as "area ruling" are often incorporated into aircraft design in order to distribute volume efficiently. Raymer (1989) presents methods for estimating wave drag in transonic and supersonic flight. These techniques compare the volume distribution of the aircraft to that of an ideal Sears-Hack body

which has the minimum possible drag for any closed end body of the same length and volume.

The effect of wave drag is to increase C_{D0} significantly at Mach numbers above 0.85 to 0.90, typically by a factor of 2.5 or more over the C_{D0} at lower velocities. Figure 4-3 shows the change in C_{D0} for several aircraft as a function of Mach number (Raymer, 1989, p. 296). As the chart shows, the drag coefficient increases rapidly for most aircraft near Mach 1. This effect is greater for aircraft designed for both subsonic and supersonic flight (such as the F-14) than for aircraft such as the B-70 that are designed primarily for supersonic flight. This effect results from the different design considerations that are incorporated into supersonic and subsonic aircraft, especially in wing design.

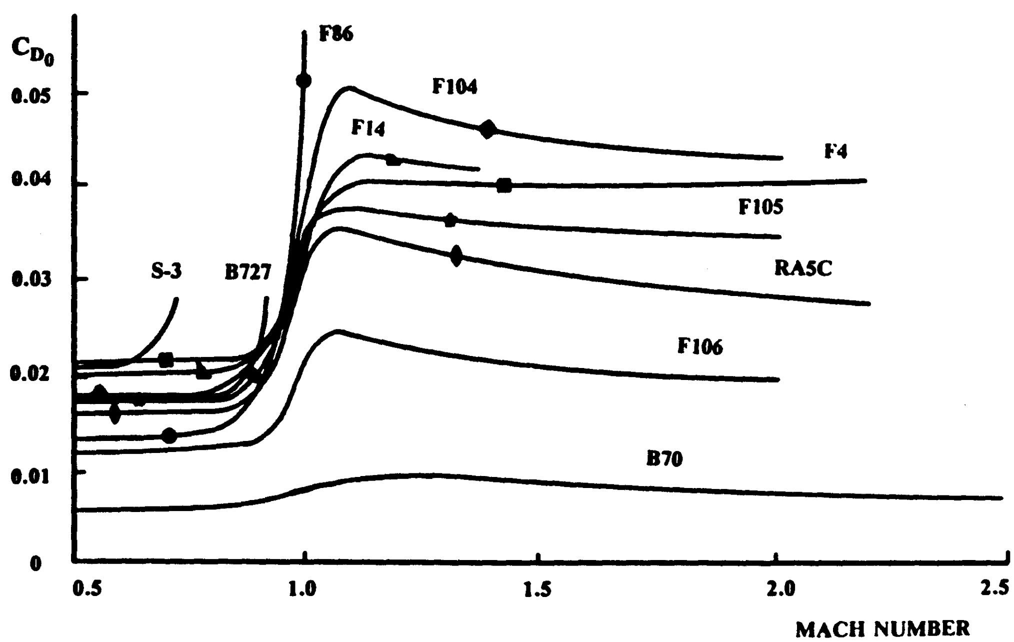

Figure 4-3. *Coefficient of Parasite Drag (C_{D0}) for Representative Aircraft Versus Flight Mach Number [From Raymer, 1989, p. 296].*

4. Lift-to-Drag Ratios:

The aerodynamic efficiency of aircraft is often defined in terms of lift-to-drag ratios. For a given operating altitude and aircraft weight, an optimal speed exists at which the aircraft's lift-to-drag ratio is maximized. The significance of this point can be seen in the Breguet range equation which relates the range that an aircraft can fly to several design parameters including lift-to-drag ratio. The Breguet range equation has the following form:

$$R = (v/SFC)(L/D)\log(W_i/W_f) \qquad (4\text{-}13)$$

where:
R = range
v = flight velocity
SFC = thrust specific fuel consumption
W_i = initial weight (at beginning of flight or flight increment)
W_f = final weight (at end of flight or flight increment)

As this equation shows, improving the lift-to-drag ratio of a given aircraft at a given speed will increase the range that the aircraft can fly (all other factors being constant). Thus, the lift-to-drag ratio of an aircraft denotes the relative efficiency of that aircraft. This fact should be apparent from the definitions of lift and drag. Since the lift generated by an aircraft is fixed by its weight, increases in lift-to-drag ratio can be achieved by decreasing the drag of the aircraft, improving its aerodynamic efficiency.

5. Changes in Lift and Drag:

The lift and drag forces acting upon an aircraft vary during the course of flight. Even if an aircraft flies at constant altitude and velocity, its weight will continue to change as fuel is burned, and thus, the lift required to maintain the aircraft in level flight will decrease. Without intervention by the pilot or control system, the aircraft will have a tendency to rise until the air density declines sufficiently to restore the equilibrium between lift and weight. This process assumes, however, that the aircraft maintains a constant angle of attack and constant thrust.

Alternatively, the lift experienced by an aircraft can be reduced by either changing the aircraft's angle-of-attack or by decreasing flight velocity. In the first case, a decrease in angle-of-attack translates into a reduced coefficient of lift. Thus, the total lift generated by the aircraft decreases. Simultaneously, the induced drag on the aircraft decreases. The overall effect on the lift to drag ratio of the aircraft will depend upon specific operating conditions. Lift may also be decreased by slowing the flight velocity of the aircraft, but maintaining a constant altitude and angle-of-attack. In this case, drag will also be affected and, in fact, the ratio of lift to drag can be improved, but the flight velocity of the aircraft will decline.

B. Commercial Requirements:

Aerodynamic analysis of commercial aircraft can produce useful insight into future requirements for commercial engines. By analyzing the performance of typical commercial aircraft, one can discern technological innovations that can decrease the direct operating cost of a airliner. The innovations with the greatest financial rewards to airlines can also be determined from aerodynamic analysis.

As demonstrated in Chapter III, commercial aviation requirements have historically been determined by cost considerations. Even during the days of regulated airfares, commercial innovations were measured in terms of their effect upon direct operating costs. In the present age, the Civil Aeronautics Board no longer establishes fares on carrier routes, and as a result cost competition has become more intense. Decisions to purchase new equipment or to modify existing equipment are consistently made on a cost basis.

Commercial aircraft are developed with payload, range, and economic efficiency as key design criteria. Different sized aircraft are designed to maximize the efficiency of transporting passengers between destinations. For given levels of traffic density along particular routes, suitably sized aircraft are selected for use. Thus, technological developments likely to improve economic efficiency can be analyzed in terms of their effect on direct operating costs of representative aircraft. In particular, the influence of new technologies upon fuel expenditure can be evaluated.

The Breguet range equation provides a suitable means for making such evaluations. This equation relates the range travelled by an aircraft to its change in weight during flight, its lift-to-drag ratio, its flight velocity, and its specific fuel consumption. In terms of these variables, the equation takes the form presented above:

$$R = (v/SFC)\ (L/D)\ \log\ (W_i/W_f)$$

The values for L/D and W_i/W_f are dictated by aircraft size and design. They are established primarily by the desired capacity of the aircraft selected to fly a particular route. These characteristics can be altered by changing the aerodynamic design of the aircraft or using new materials for construction. As such, they reflect the state-of-the-art in aircraft design at any given point in time.

Engine design, on the other hand, has its greatest influence on aircraft velocity and SFC. While engine weight and drag can factor into the L/D and weight considerations, for large commercial jet liners the effect of the engine upon these factors is small compared to the contribution of the airframe. Engine thrust and efficiency are directly related to velocity and SFC, however. These factors can influence the profitability of an airliner by increasing the range of its aircraft, or conversely, decreasing the amount of fuel needed to travel a desired range. As the Breguet equation shows, either increasing v or decreasing SFC will increase the range of an aircraft. Similarly, increasing v or decreasing SFC will allow an aircraft to fly a constant range with a lower value of W_i/W_f. Since the difference between W_i and W_f for a commercial airliner is equal to the fuel burned during flight, changes in v and SFC translate into changes in fuel burn and, hence, direct operating costs for flights of constant range.

The effect of thrust upon airline profitability has long been recognized in the airline industry. As was demonstrated in Chapter III, the jet airliner became an economical aircraft only when the thrust generated by jet engines became sufficient to allow high flight velocities. Further increases in thrust, however, do not appear to increase the profitability of present aircraft. Present airliners operate at cruise speeds between Mach 0.75 and 0.86. At higher velocities, transonic compressibility effects increase and wave drag grows significantly. The increase in C_{D0} with Mach number for a Boeing 727-200 can be seen in Figure 4-4 which is adapted from Roskam (1987, p. 123). Whereas the coefficient of drag at Mach 0.76 is only 0.0176, C_{D0} at Mach 0.9 increases to 0.0240.

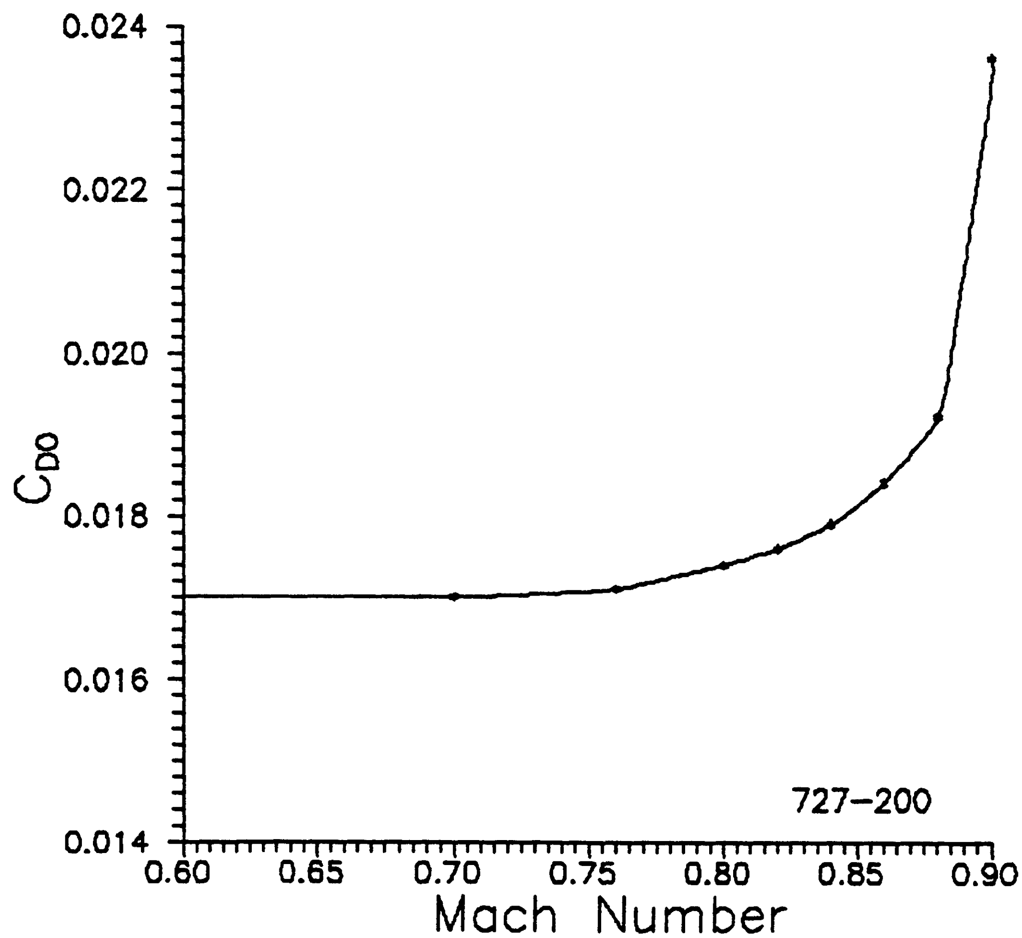

Figure 4-4. *Coefficient of Parasite Drag (C_{D0}) for the Boeing 727-200 Versus Flight Mach Number [From Roskam, 1987, p. 123].*

To demonstrate the effects of this large increase in drag upon aircraft performance, the range of the 727-200 was computed as a function of Mach number using the values of C_{D0} from Figure 4-4 and the aircraft physical data shown in Table 4-1. Values in this table were taken from Taylor (1990) with the exception of the Oswald Span Efficiency Factor which comes from Roskam (1987, p. 123). This curve was plotted assuming the aircraft maintains a constant speed throughout the flight and adjusts its angle of attack accordingly. Values of L/D were recalculated for each 1/10 of the fuel burned. The flight altitude was held constant 30,000 feet, consistent with the thrust-generating capability of the JT8D engines. SFC was assumed to remain constant at 0.81 lb/lbt/hr regardless of flight speed. The calculations also assumed that 2% of the fuel is burned prior to cruise (during warm-up, taxi, and takeoff, etc) and another 8% is kept in reserve, consistent with general airline operating principles. As Figure 4-4 demonstrates, the 727 achieves its maximum range of 2450 nautical miles (nm) at Mach number of approximately 0.76. Further increases in flight speed degrade this range rapidly. At Mach 0.9, for example, the 727-200 can fly only 1825 nm. This large reduction in maximum range results from the increase in C_{D0} at high speeds. Between Mach 0.76 and 0.90, maximum lift-to-drag at the beginning of the flight decreases from 16.89 to 11.17, overwhelming any gains resulting from increased flight speed.

Such results are not characteristic only of small commercial transports; they apply similarly to large commercial wide-body jets such as the Boeing 747 as well.

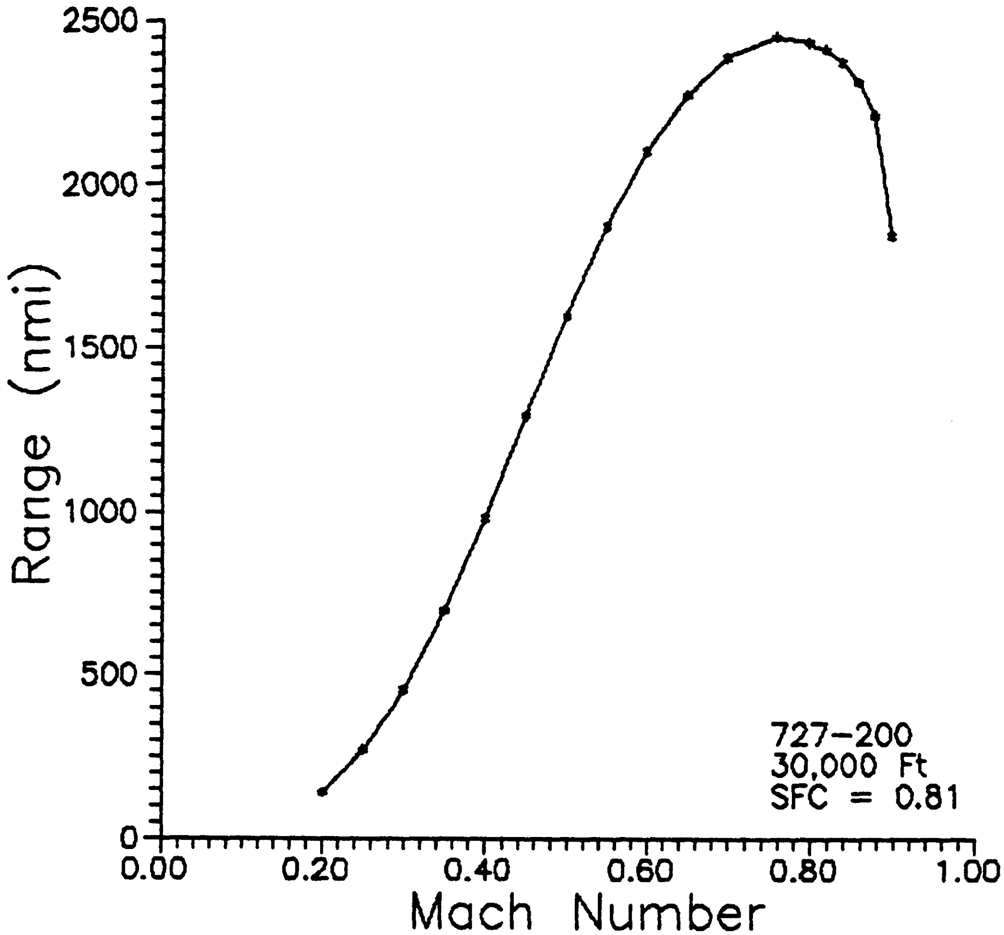

Figure 4-5. ***Maximum Range of the Boeing 727-200 Versus Mach Number at 30,000 Feet, Assuming Constant Flight Speed.***

Table 4-1
Specifications for Boeing 727-200

Parameter	Value
Wing Reference Area (ft^2)	1700
Wing Span (ft)	108
Aspect Ratio	6.86
Empty Weight (lb)	102,300
Payload Weight (lb)	39,500
Fuel Weight (lb)	50,500
Takeoff Weight (lb)	190,500
Altitude (ft)	30,000
SFC (lb/lb/hr) [JT8D-7]	0.81
Oswald Span Efficiency Factor	0.90

Table 4-2
Specifications for Boeing 747-200

Parameter	Value
Wing Reference Area (ft^2)	5500
Wing Span (ft)	195.75
Aspect Ratio	6.97
Empty Weight (lb)	380,800
Payload Weight (lb)	145,700
Fuel Weight (lb)	306,500
Takeoff Weight (lb)	833,000
Altitude (ft)	35,000
SFC (lb/lb/hr) [CF6-80C2]	0.61
Oswald Span Efficiency Factor	1.02

Though the Boeing 747 has a higher maximum lift-to-drag ratio than the 727 at cruise (over 21 at Mach 0.70), its optimum flight speed is limited by compressibility effects to speeds of approximately Mach 0.83. Figure 4-6 shows the change in C_{D0} for the 747-200 versus Mach number as given by Roskam (1987, p. 124). Whereas the curve is relatively flat for Mach numbers below 0.75, it begins to rise rapidly for Mach numbers above 0.80. As a result, maximum flight range is severely reduced at high Mach numbers. Figure 4-7 shows the result of calculations of the maximum range of the 747-200 versus Mach number using the data in Table 4-2 which again is derived from Taylor (1990) with the exception of the Oswald span efficiency factor which is taken from Roskam (1987, p. 124). The analysis makes the same general assumptions as described above for the 727 analysis. As the curve demonstrates, the range of the 747 decreases at speeds greater than Mach 0.83. As with the 727, the change in the range of the 747 results from the rise in C_{D0} as flight velocity is increased.

This analysis demonstrates that present commercial airliners have little to benefit in the way of speed due to large increases in engine thrust. As experience with the Concorde has demonstrated, new airframes designed for supersonic speeds may fair no better (Gunston, 1987, p. 77). From the perspective of increased flight speeds, increased thrust appears detrimental to commercial operations.

Nevertheless, higher thrust engines can power larger, heavier aircraft. Increases in thrust would allow current aircraft to be stretched so that they may carry more passengers. Alternatively, larger engines could power new, larger

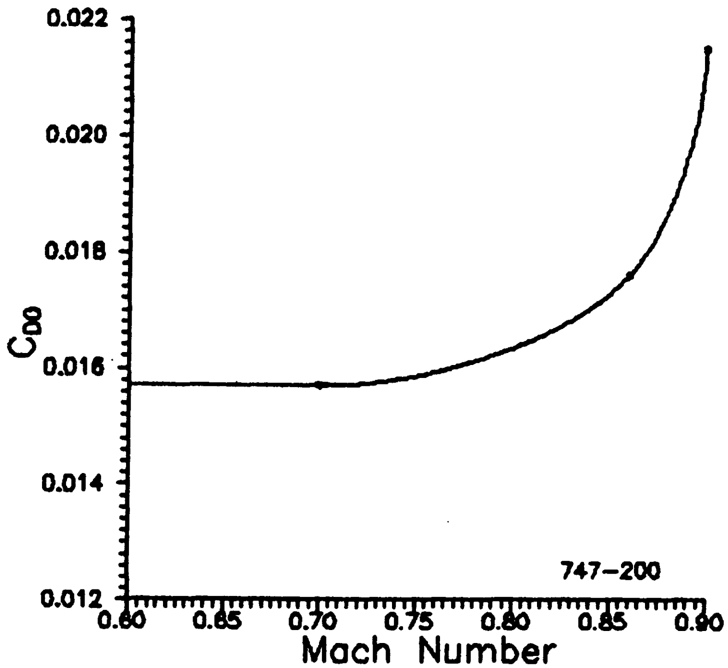

Figure 4-6

Coefficient of Parasite Drag (C_{D0}) for the Boeing 747-200 Versus Flight Mach Number [From Roskam, 1987, p. 124].

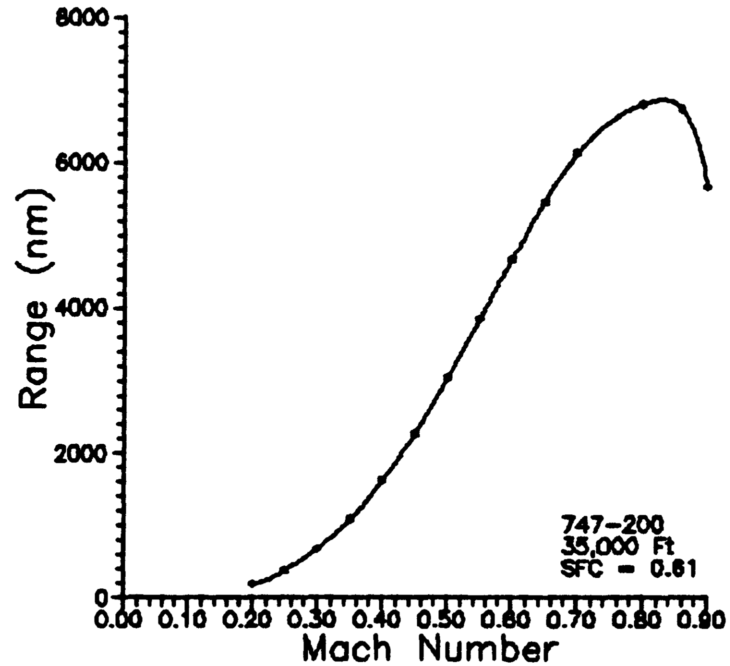

Figure 4-7

Maximum Range of the Boeing 747-200 Versus Mach Number at 35,000 Feet, Assuming Constant Speed Throughout the Flight.

aircraft. In fact, a number of airlines are considering the use of bigger aircraft to reduce airport congestion problems (Markillie, 1988, p. 21). Several new, large aircraft, including the Airbus 330 and the Boeing 777 which is presently under development, are designed for only two engines. These aircraft push current engines to their limit and may necessitate the development of new engines should they grow in size over their operational lifetime. At present, no aircraft manufacturer nor no airline is designing another commercial jet transport larger than the Boeing 747 (Gunston, 1987, p. 77); however both Airbus and Boeing are contemplating the design of a 600-passengers transport to serve the Pacific Rim ten or more years from now (O'Lone, 1990, p. 80). These aircraft will almost undoubtedly require the development of new, higher thrust turbofan engines.

Airlines can clearly benefit from reductions in SFC. As long as such reductions can be achieved without significantly increasing the drag or the weight of the aircraft, reductions in SFC will allow aircraft to fly farther with the same amount of fuel or to fly a constant range while burning less fuel overall. To demonstrate this effect, the increase in aircraft range resulting from a decline in SFC was computed from the Breguet range equation. Figure 4-8 shows the result of these calculations, plotting the percent increases in maximum range that would result from percentage improvements in engine SFC. This data is valid for both the 727-200 and the 747-200 as well as other aircraft. As shown, a 1% decrease in SFC results in a slightly greater than 1% improvement in maximum range, assuming as above, a constant flight speed. With a 15% improvement in SFC, a figure widely cited as feasible for turbofan engines, maximum range could be increased by 17.5%.

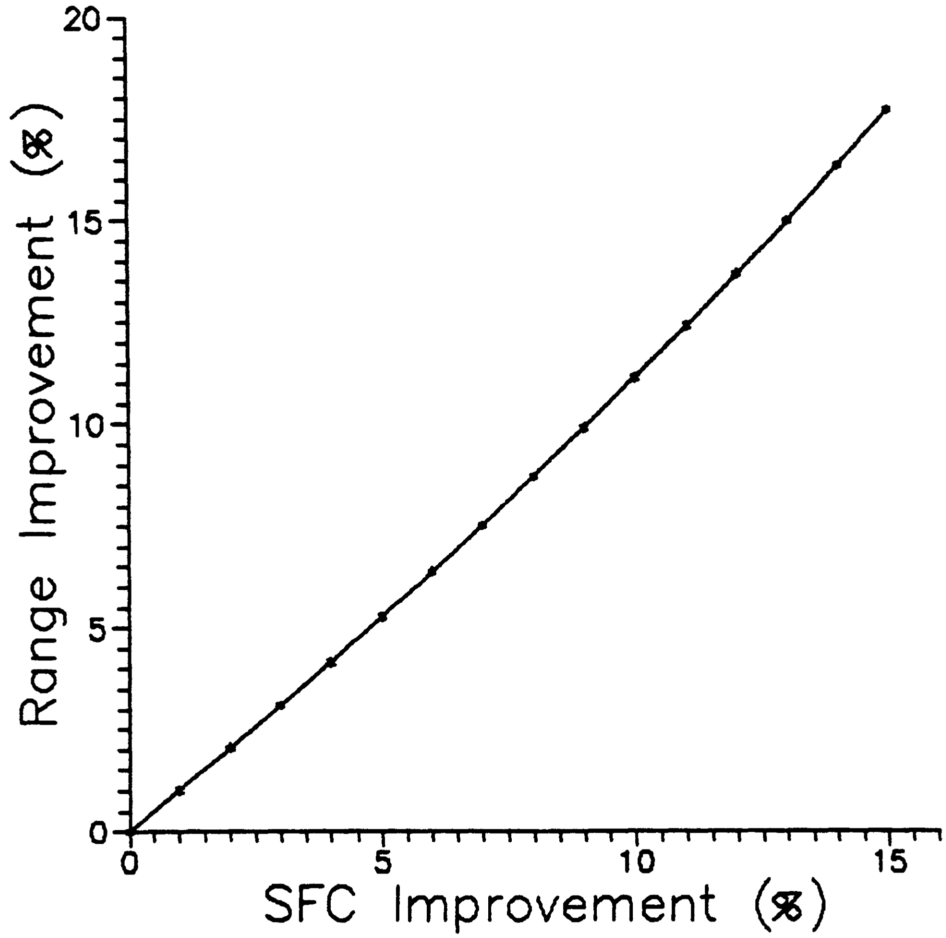

Figure 4-8. ***Percent Improvement in Maximum Flight Range Resulting from Percentage Improvements in Engine Specific Fuel Consumption.***

Gains in maximum range could translate into cost savings for airlines in that they would allow smaller aircraft to fly some longer routes now served only by larger aircraft. On some of these routes passenger traffic is low enough that either few flights can be scheduled or large planes must fly with only a fraction of their seats filled. Operation of smaller aircraft on these routes may prove more profitable since the aircraft would be flying closer to full capacity.

Improved SFC would provide greater gains to airlines in that it would allow them to fly their current routes while burning less fuel. In order to estimate the size of such savings, the Breguet range equation was used to calculate the amount of fuel burned by the 727-200 and the 747-200 on flights of varying range for different levels of improvement in SFC. Flight speed was assumed to be unaffected by changes in SFC. The results of the analysis for the 727 and 747 are plotted in Figures 4-9 and 4-10, respectively. With its current engines, the 727 burns approximately 38,000 lb of fuel on a 2000 nm trip. With only a 5% improvement in SFC, fuel burn could be reduced to under 36,000 pounds for the same trip saving 2000 lb of fuel. Larger reductions in SFC provide proportional reductions in fuel burn so that for a 15% reduction in SFC, fuel burn could be as low as 32,000 lb. The 15% reduction in SFC represents a reasonable estimate of reductions in SFC for turbofan engines. Additional reductions in SFC could be achieved with turboprop engines. Several hybrid turboprop engines, called propfans, have been tested on demonstration aircraft such as the MD-80. Estimates of SFC reductions available with these engines range between 25% and 60%, with 40% being a commonly accepted value (Miller, 1987, p. 30; Saunders and Glassman, 1985, p. 4; Gray and Conliffe, 1990, p. 33). Because of limitations on blade rotation rates and their low specific thrust, these engines cannot generate enough total thrust for widebody jets and can be used only on short-medium range airliners. Figure 4-9 shows the effect such an engine would have on fuel burn with the 727. Fuel burn could be reduced to approximately 23,000 pounds with propfan engine, saving over 15,000 lbs of fuel.

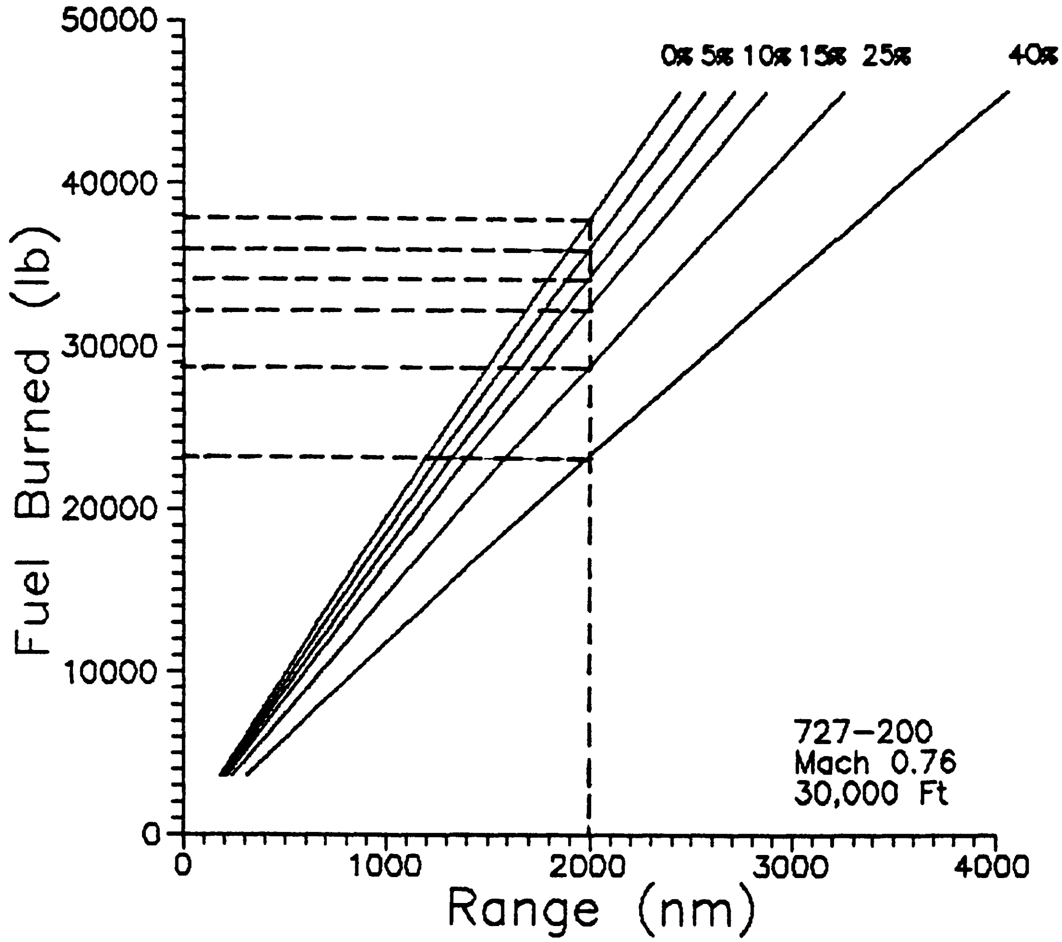

Figure 4-9. *Reduction in Fuel Burned by a Boeing 727-200 Versus Flight Range for Percentage Improvements in Engine Specific Fuel Consumption (SFC).*

Similar results are achieved with the 747. Although the 747 is too large to be powered by present propfans, reductions of 15% in SFC would still be available with turbofan technology. As Figure 4-10 demonstrates, such an improvement would decrease fuel burn on a 5000 nm route from 215,000 pounds to 185,000 pounds.

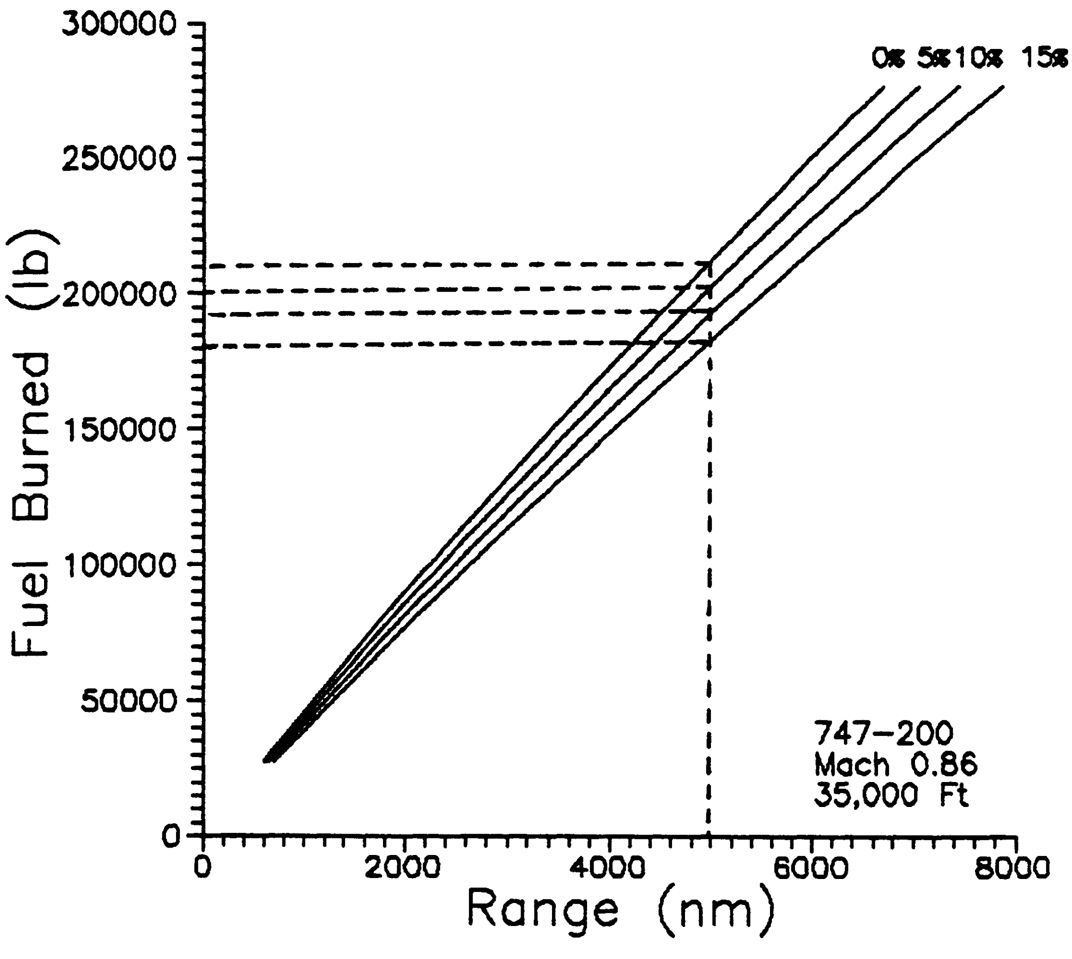

Figure 4-10. ***Reduction in Fuel Burned by a Boeing 747-200 Versus Flight Range for Percentage Improvements in Engine Specific Fuel Consumption (SFC).***

The actual savings an airline would achieve with such reductions varies according to the price of fuel--a value which has been highly unstable over the past two decades. Between 1975 and 1989, the cost of jet fuel has increased from \$0.29 to \$0.60 per gallon in nominal terms. At the same time the fraction of an airline's total cash operating expenses represented by fuel costs has varied from a maximum of 29.7% in 1980 to a low of 14.9% in 1989. Hence, the value of fuel savings has varied and will continue to vary with the price of fuel over time.

The uncertainty associated with fuel prices complicates long-term decision making for airlines, aircraft manufacturers, and engine manufacturers. As could be expected, interest in fuel-saving technologies waxes and wanes with the variation in fuel prices. Nevertheless, the high percentage of operating costs represented by fuel and the strong variation in fuel prices place great emphasis on lowering airliner SFC. Not only will such reductions decrease the total cost of fuel to airlines and decrease their direct operating costs proportionally, but they will allow airline profitability to become less susceptible to changes in fuel prices.

Therefore, commercial engine development will most likely progress along two routes. First, engine manufacturers will attempt to increase the efficiency of high-bypass ratio turbofan engines. These engines, though large and heavy, are the only types of engines presently capable of producing sufficient thrust to power large airliners. Figure 4-11 shows the maximum thrust required to maintain the Boeing 747-200 in steady flight as a function of Mach number. This curve was calculated using the physical data in Table 4-2 and the aerodynamic drag data in

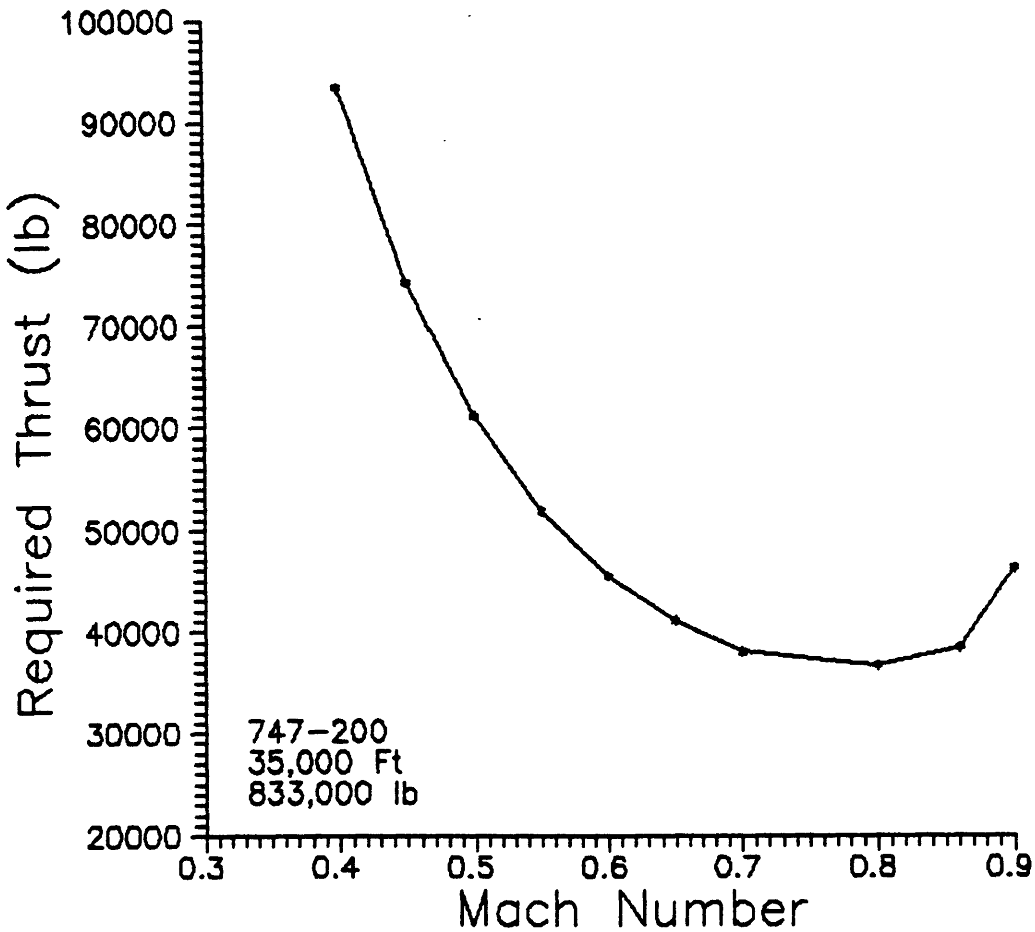

Figure 4-11. *Total Thrust Required to Maintain a Fully-Loaded 747-200 in Level Flight at 35,000 Feet Versus Flight Mach Number.*

Figure 4-6. As shown, an aircraft such as the 747 flying at Mach 0.8 requires almost 40,000 pounds of total thrust. Moreover, away from the optimal cruise point, greater amounts of thrust are needed. High-bypass ratio turbofans are, at present, the only engines capable of generating such large amounts of thrust at cruise with low enough values of SFC to allow long range flight. Further improvement in SFC would make these engines even more cost-effective for airlines to operate.

In addition, commercial interests will likely pursue further development of propfan engines. Though these engines are limited in thrust and could power only short-medium range airliners to speeds of approximately Mach 0.80, they offer significant decreases in SFC. To demonstrate this fact, the minimum thrust required to maintain a 727-size aircraft in level flight at operational speeds and altitudes was calculated using the data in Table 4-1 and Figure 4-4. Figure 4-12 shows the result of these calculations for the Boeing 727-200 in level flight at 30,000 feet. At a speed of Mach 0.76, this aircraft requires only 11,500 pounds of total thrust to maintain level flight. Thus, for a twin-engine aircraft, each engine need only generate 6,000 pounds of thrust (though additional thrust would be required for off-design cruise and for climb). A tri-jet such as the 727 requires only 4,000 pounds of thrust per engine. These values are commensurate with the anticipated thrust of propfan engines which have sea-level static thrust ratings between 20,000 and 25,000 pounds as does the JT8D engine currently powering the 727. As these engines potentially have SFCs 40% lower than present high-bypass ratio turbofans, they represent a possible alternative to the high-bypass ratio turbofans used on most present short- to medium-range transports.

C. Military Interests:

The military has a variety of uses for aircraft. As opposed to the commercial airline industry which uses its aircraft solely to ferry passengers between destinations, the military has varied missions for different types of aircraft:

transports, bombers, and fighter/attack aircraft. Thus, an analysis of likely requirements for future military aircraft must examine each of these areas independently.

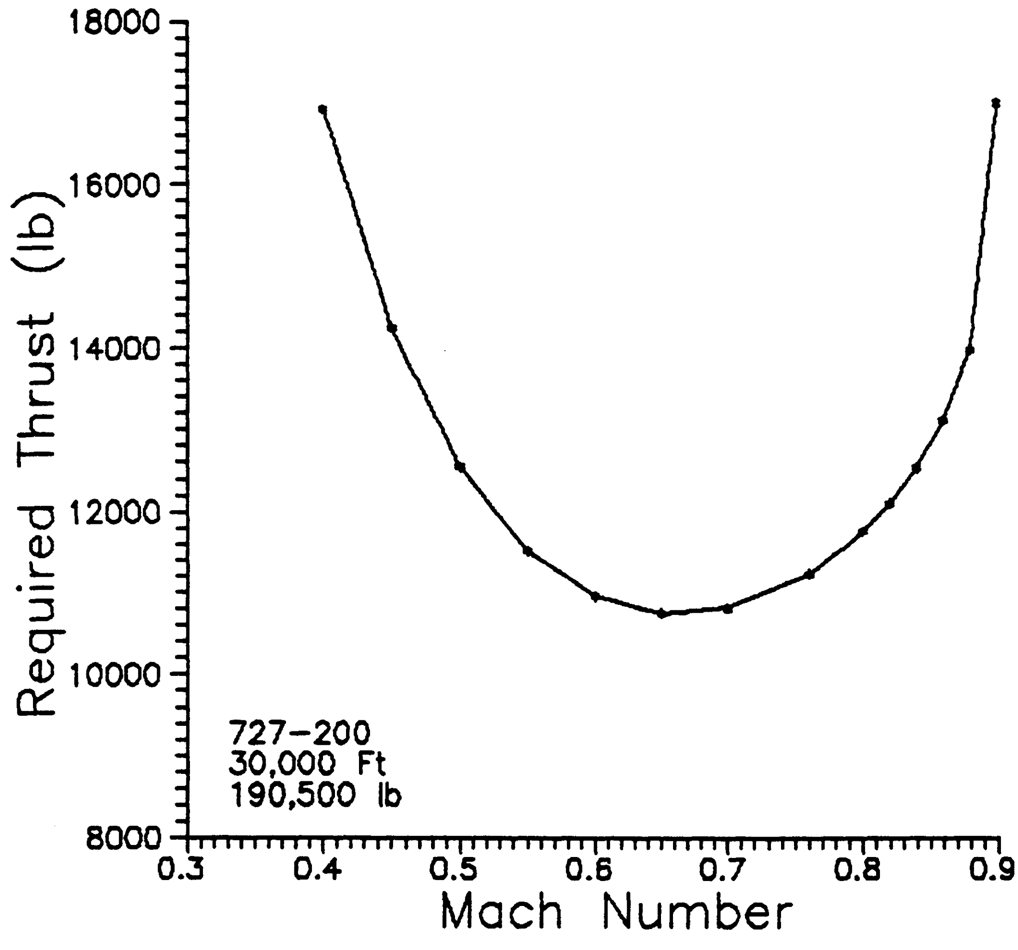

Figure 4-12. Total Thrust Required to Maintain a Fully-Loaded 727-200 in Level Flight at 30,000 Feet Versus Flight Mach Number.

1. Military Transports:

The military operates a number of transport and cargo aircraft that span a wide range of sizes from the 10,000 pound empty-weight C-20 to the 374,000 pound empty-weight C-5B. Of these, only the KC-135, VC-137, C-141, C-5, KC-10A and the VC-25A weigh over 100,000 pounds and are comparable to jet airliners. Nevertheless, these aircraft have played an important part in the development of passenger aircraft and their engines. The KC-135, for example, is a tanker version of the Boeing 707, the first U.S. jetliner. The military's decision to purchase the KC-135 paved the way for the production of the 707. Work on the engines for the C-5, as described in Chapter III, resulted in the development of the high-bypass turbofan engines now used on large commercial passenger transports.

Like commercial airliners, military transports gain little advantage from increased velocity. The two primary design considerations in transport design are range and payload. Increased speed itself has little or no tactical utility for transports. Transports do not typically penetrate enemy air defenses and so have no need for supersonic dash capability. Nor do transports need to reduce their travel time between destinations. Airlift is a process that takes weeks or months to accomplish; decreasing the flight time of a single transport would offer little additional capability to the military.

Increased velocity is, in fact, detrimental to military transports. As with the airliners, the range of military transports decreases as Mach numbers approach 1.0. Because of their shape, C_{D0} for large military transports such as the C-141 and the C-5 begins to increase dramatically at Mach numbers as low as 0.70. For the C-5, C_{D0} increases from 0.016 to 0.039 as Mach number increases from 0.70 to 0.87 (Roskam, 1987, p. 126).

Trends in transport development are difficult to discern. As the present fleet of U.S. military transports spans a wide range of sizes, development seems unlikely to focus either on increasing payload capability or on filling in holes in present capacity. Rather, development may focus upon the replacement of older aircraft. The C-17 represents a case in point. With an empty weight of 269,000 pounds, a maximum takeoff weight of 580,000 pounds, and a payload capacity of 172,000 pounds (Jane's, 1990), the C-17 is being designed as a long-range, heavy lift transport to replace the C-141. Given the wide-ranging capabilities of the present transport fleet, it is unlikely that another major transport program will be undertaken in the near future.

Engines for transport-sized aircraft have already been developed. Thus, replacement of older military transports is unlikely to generate novel engine requirements that necessitate new R&D programs. While the military could benefit from replacing their transport engines with more fuel efficient engines, the military will probably not fund the development of new high-bypass ratio turbofans. The commercial motivation for designing such engines is strong and will probably not require additional military support. Transport aircraft will most likely continue to adapt commercial engines to their purposes. The C-17, for example, will use Pratt & Whitney PW2000 engines. These engines were developed for commercial airliners, but had adequate thrust to power the C-17. As these engines were developed to reduce SFC on commercial airliners, the military had little incentive to develop more efficient engines for the C-17.

2. Military Bombers:

Military bombers, like military transports, are designed for long-range flight and heavy payloads. Bombers such as the B-52, B-1B, and B-2 are all designed with intercontinental ranges and payloads of over 40,000 pounds. Flight velocity is a lesser priority. As with the commercial airliners, bombers lose range capability at transonic and supersonic velocities because of the increase in C_{D0} at speeds above Mach 0.8. Thus, bombers trade off supersonic cruise velocity for range. Even the B-1B bomber which has a supersonic dash capability is designed for subsonic cruise to preserve its range capability.

As a result of range and payload requirements, development of new bomber engines should focus on lowering specific fuel consumption. As demonstrated in Figure 4-8 earlier, a 1% improvement in SFC translates into a greater than 1% increase in range. For long range aircraft like military bombers, large increases in total range can be achieved even by small percentage improvements in SFC. This effect can be demonstrated by considering the B-2 bomber. An analysis of which was conducted for this study. Although lift, drag, and weight data for the B-2 have not been released publicly, values for these parameters were estimated from various sources and are shown in Table 4-3. Weights for the B-2 were estimated from Taylor (1990) and Aviation Week (Bond, 1989, pp. 30-31).

Table 4-3
Specifications for the Northrop B-2 Bomber

Parameter	Value
Wing Reference Area (ft^2)	5100
Wing Span (ft)	172
Aspect Ratio	6.29
Empty Weight (lb)	130,000 (est.)
Fuel Weight (lb)	170,000 (est.)
Takeoff Weight (lb)	350,000
Altitude (ft)	35,000
SFC (lb/lb/hr)	0.80 (est.)
Oswald Span Efficiency Factor	0.70
C_{D0} (Subsonic)	0.0072 (est.)

The Oswald span efficiency factor was estimated using equation 4-11 presented earlier in this chapter. The subsonic C_{D0} of the B-2 was estimated using the component buildup method described in Raymer (1989, p. 279). Transonic effects were not included in this analysis, so the value shown in Table 4-3 is valid only up to Mach 0.8. The value shown for C_{D0} is in close agreement with a value derived independently by Roskam (1991, p. 18). The B-2's range capability at cruise at 35,000 feet was calculated with the Breguet range equation using these values. The result is shown in Figure 4-13. Assuming 2% of the B-2's total fuel is used in taxi, takeoff, and climb and that 8% is maintained as a reserve, the B-2 appears to have a maximum range of approximately 7400 nm at a speed of Mach 0.8. An increase in flight velocity would decrease the range of the B-2 because of wave drag effects, but an improvement in SFC of 15% could increase its range capability by 17.5% to 8510 nm.

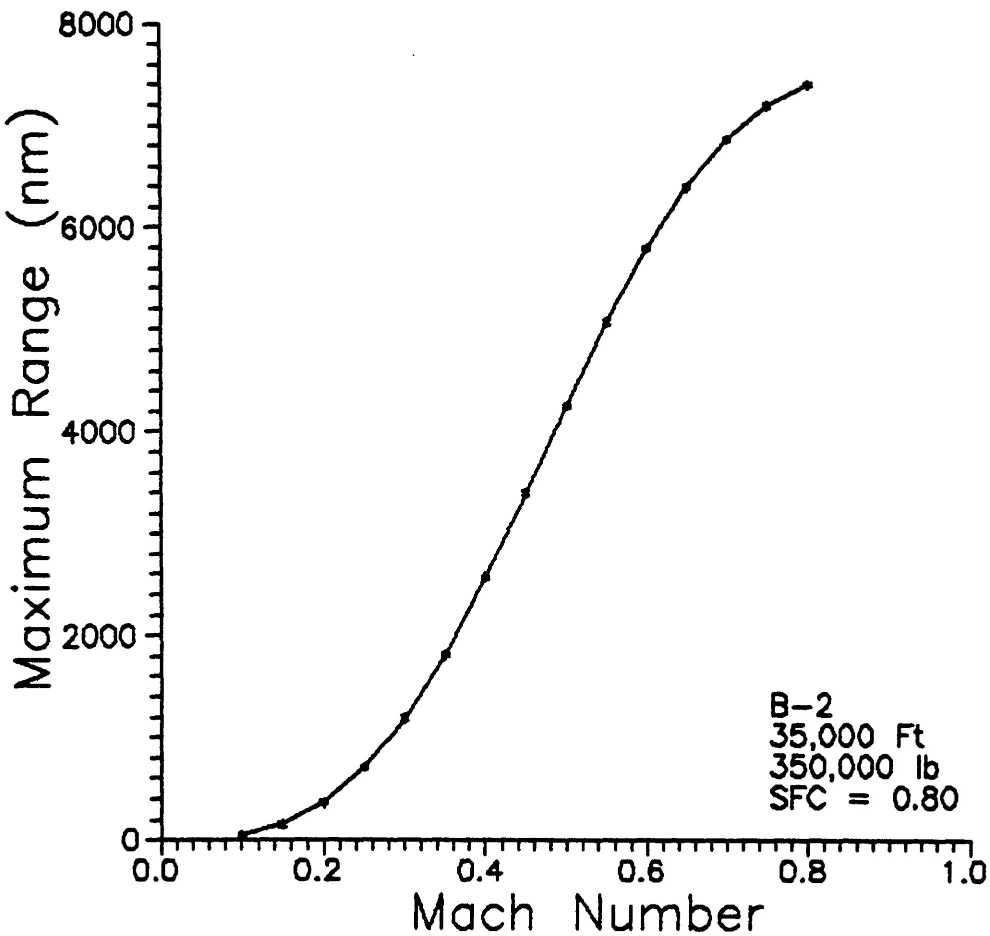

Figure 4-13. ***Estimated Maximum Range of the Northrop B-2 Bomber at 35,000 Feet Assuming a Constant Flight Velocity.***

Despite the advantages of improved SFC, other design considerations limit the SFC values achievable on bomber aircraft. Bomber engines must generate large quantities of thrust. A bomber such as the B-2 weighs 350,000 pounds fully loaded. The B-1 and the B-52 weigh even more. Using the figures shown in Table 4-3, the thrust required to maintain the B-2 in level flight can be calculated for a range of Mach numbers. Figure 4-14 summarizes the results of this analysis. As shown, the B-2 requires 16,000 pounds of total thrust to maintain level flight at 35,000 feet and a speed of Mach 0.80. At lower velocities such as Mach 0.5, the thrust requirement increases to over 20,000 pounds.

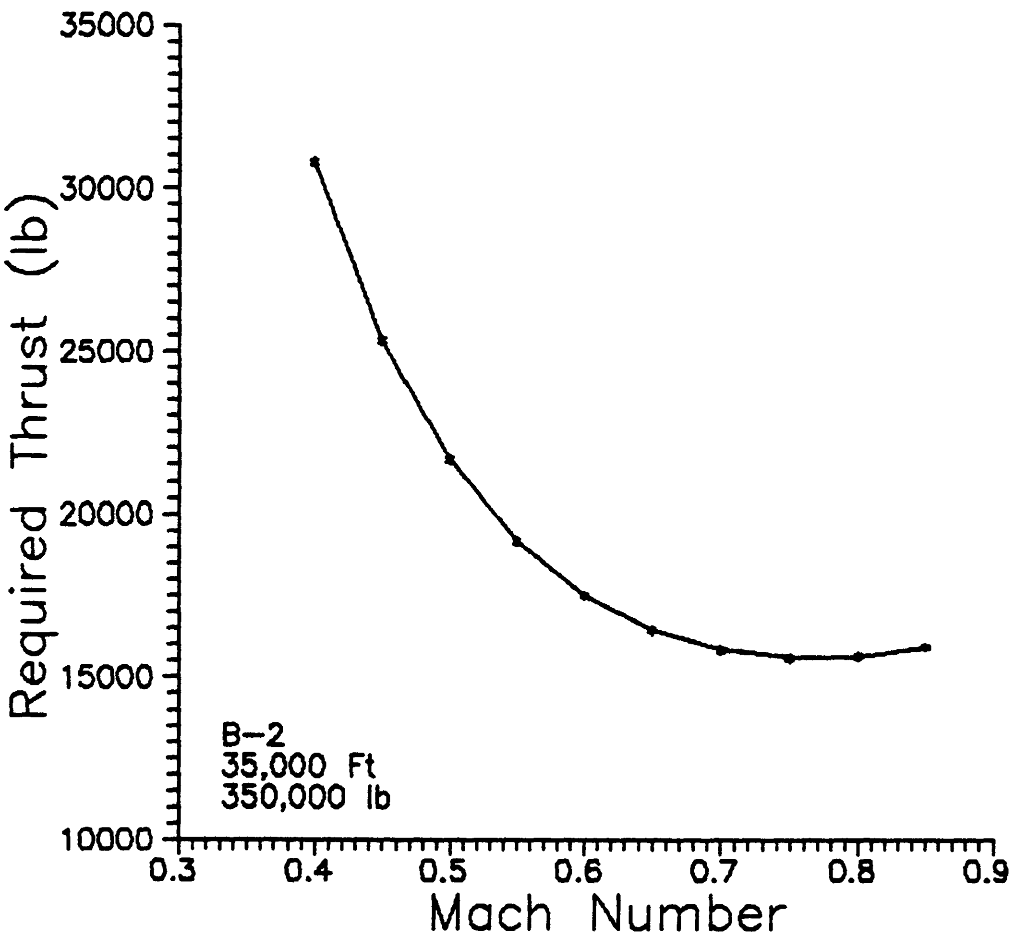

Figure 4-14. ***Total Thrust Required to Maintain the B-2 Bomber in Level Flight at 35,0000 Feet Versus Mach Number, Assuming a Maximum Take-off Weight of 350,000 Pounds.***

Given the high thrust and low SFC desired for long-range bombers, the likely choice of engine would be a high-bypass-ratio turbofan. As will be shown, such engines are too large to be incorporated onto modern bombers. Though the exact form of future bombers cannot be determined at this time, the B-1 and B- 2 characterize likely requirements. Both are designed with survivability as a major design consideration. In the B-1, survivability is achieved primarily through its supersonic dash capability which is designed to minimize the aircraft's exposure to hostile air defenses. The B-1 also incorporates stealth features to reduce its radar cross section. In the B-2, survivability is achieved almost exclusively through stealth design characteristics that are intended to prevent or delay detection by enemy sensors. Future bombers will most likely incorporate one of these two criteria into their design.

Supersonic speed and stealth both require engines with small frontal areas. As velocities approach the speed of sound, the drag caused by engine nacelles increases rapidly as does the C_{D0} of the aircraft itself. This drag degrades the performance of the aircraft and increases the stresses transmitted to the engine mountings. Thus, engines for supersonic aircraft are not mounted away from the fuselage on under-wing pylons; instead they are mounted against the body of the aircraft as on the B-1 or are integrated into the airframe as on fighter aircraft. Stealth requirements place further restrictions on engine mounting. Engine nacelles and fan blades can generate large radar returns when an aircraft is viewed at forward angles. The hot exhaust of the engine can potentially be detected at long range by sophisticated infrared surveillance sensors. Thus, engine fan blades must be shielded and the engine exhaust must be mixed with cooling air to reduce their radar and infrared signatures, respectively. In effect, such requirements dictate that engines be mounted conformally. In the case of the B-2, the engines are mounted within the wing of the aircraft. Thus, the size of the engine is limited by the dimensions of the aircraft wing or body.

Such size constraints place a high demand on specific thrust. Because the inlet size of the engine is limited, engines with low specific thrust such as high bypass ratio turbofans cannot ingest a large enough mass flow of air to generate the high levels of thrust required by large bombers. Only low-bypass ratio turbofans and turbojet engines can generate adequate thrust from a limited mass air flow. This effect is demonstrated in Figure 4-15 which plots the cross sectional area required to generate 6500 pounds of thrust at 35,000 feet versus the bypass ratio of the engine. This calculation assumes an engine core with a constant overall compression ratio of 30 and a turbine inlet temperature of 2600° Fahrenheit, similar to the F118 engine that powers the B-2 (Gal-Or, 1990, p. 206). As can be seen in the figure, an increase in bypass ratio from one to four increases the required inlet area of the engine by more than a factor of two. Since area is proportional to radius squared, the inlet radius must be increased by over 1.4 times to accommodate the larger bypass ratio.

The larger inlet areas required for higher bypass ratio engines limits their applicability to bomber aircraft. However, as higher bypass ratios imply improved specific fuel consumption for given values of turbine inlet temperature and

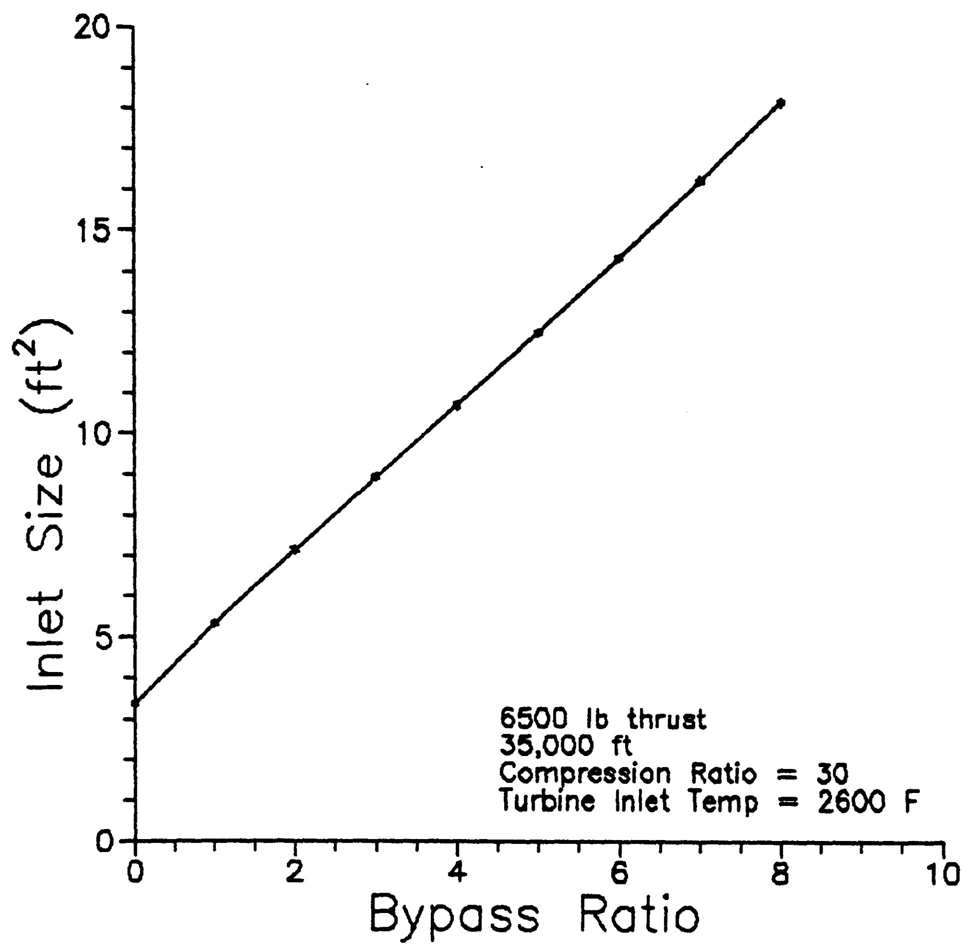

Figure 4-15. ***Inlet Size Required to Generate 6,500 Pounds of Thrust From a Turbofan Engine at 35,000 Feet Versus Engine Bypass Ratio.***

compression ratio, the inlet size requirement can be viewed as a constraint on SFC. Inlet size must be traded off against engine efficiency. In order to explore this tradeoff, the SFC associated with each bypass ratio in Figure 4-15 was computed and plotted against the corresponding inlet area requirement. This tradeoff is characterized in Figure 4-16 which plots inlet size versus SFC for the same engine examined above. In effect, the *x*-axis of Figure 4-15 has been modified to show not bypass ratio per se, but the SFC available at a given bypass ratio. As the figure demonstrates, further decreases in engine SFC can be achieved only if the engine inlet size is increased. By establishing a maximum allowable inlet size, SFC is limited to higher values.

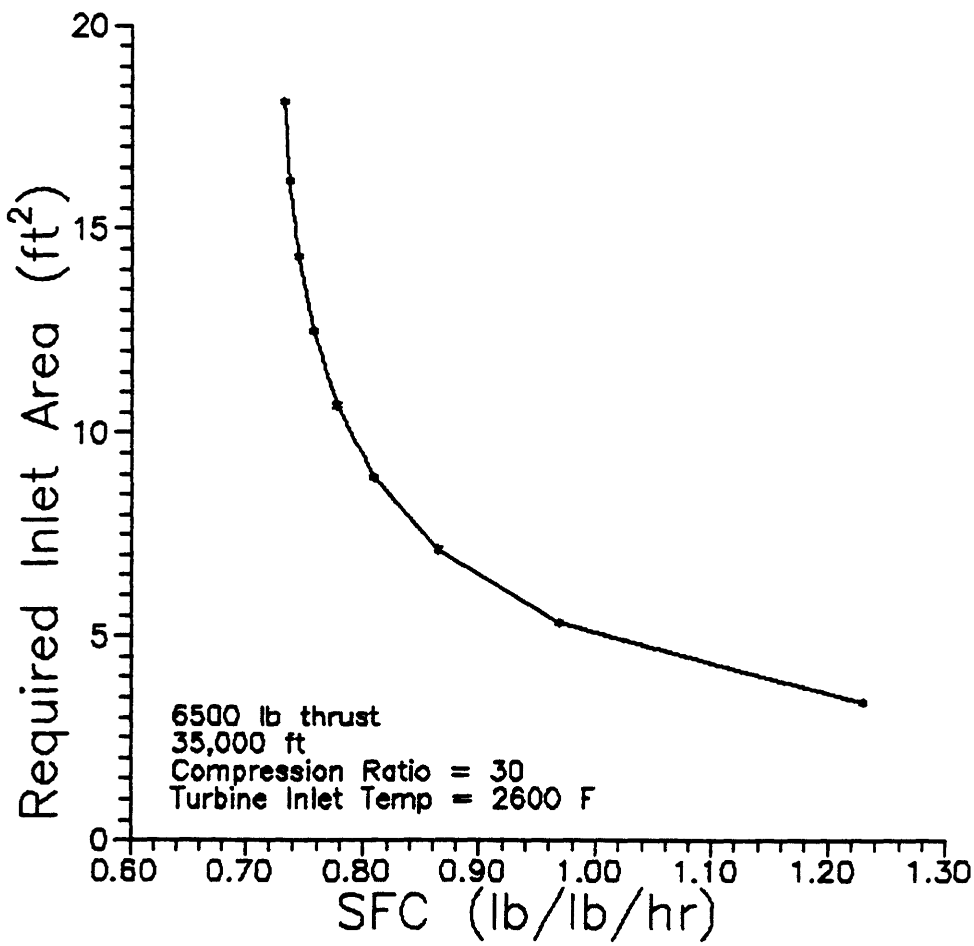

Figure 4-16. *Tradeoff Between Specific Fuel Consumption (SFC) and Required Inlet Area for a Turbofan Engine With Varying Bypass Ratio.*

Improvements in SFC can be achieved without unnecessarily increasing required inlet area if higher specific thrust engine cores are be developed for strategic bombers. With high enough specific thrust, the core can generate sufficient total thrust to power large aircraft with smaller mass airflows than present engines. Thus, the size of the core can be reduced. If the size of the overall engine were kept constant, the bypass ratio of the engine would be increased, thereby reducing the SFC of the engine.

These considerations imply that development of new bomber engines will be directed toward designing engine cores with greater specific thrust. These cores could then become the basis for higher bypass ratio engines with lower SFCs than present engines with equal thrust. Alternatively, the cores could be used to construct low bypass ratio engines with SFC equal to present engines, but with greater thrust. The higher thrust engines would allow larger, heavier bombers to be developed which could potentially carry more fuel and hence have an improved range capability. Stealth considerations, however, may preclude the development of such large aircraft.

3. Fighter/Attack Aircraft:

Much military emphasis is placed upon the development of fighter/attack aircraft (hereafter referred to simply as fighter aircraft). Over the past two decades, a variety of such aircraft have been developed for all branches of the armed forces. These aircraft include the F-14, F-15, F-16, F-18, and the ATF presently in a prototype stage. Unlike the commercial sector which has historically placed primary emphasis on cost considerations, the military has continually sought to increase the combat performance of its fighter aircraft. Thus, while commercial aircraft speeds have leveled off at approximately Mach 0.80 - 0.85, the maximum speed of military aircraft has continued to grow past Mach 2.0 (Aviation Week, 1991b, p. 106).

Increased maximum velocity has particular military utility for fighter aircraft. Such speeds allow these planes to intercept targets quickly in an offensive role, and play a major role in ensuring the survivability of these aircraft. With high velocity capability, these aircraft can minimize their time in enemy air defense coverage and can outmaneuver hostile fighter aircraft.

Requirements for supersonic velocity place great demands on thrust. As with commercial aircraft, the coefficient of drag for fighter aircraft increases rapidly at Mach numbers approaching 1. Figure 4-17 shows the change in C_{D0} versus Mach number for the F-16 fighter. This data derives from actual flight tests of the F- 16 prototypes (Webb, 1977, p. 19-11). As shown, C_{D0} increases from 0.20 to 0.42 in the transonic region. At Mach numbers greater than Mach 1.2, C_{D0} levels off at approximately .041. In order to demonstrate the effect of increasing drag upon engine requirements, the thrust required to maintain the F-16 in level flight was computed. This computation was performed using drag data from Figure 4-17 and using physical data from Table 4-4. With the exception of the Oswald span efficiency factor, all data was derived from Taylor (1990). The Oswald span efficiency factor was estimated by matching the drag polar computations with a

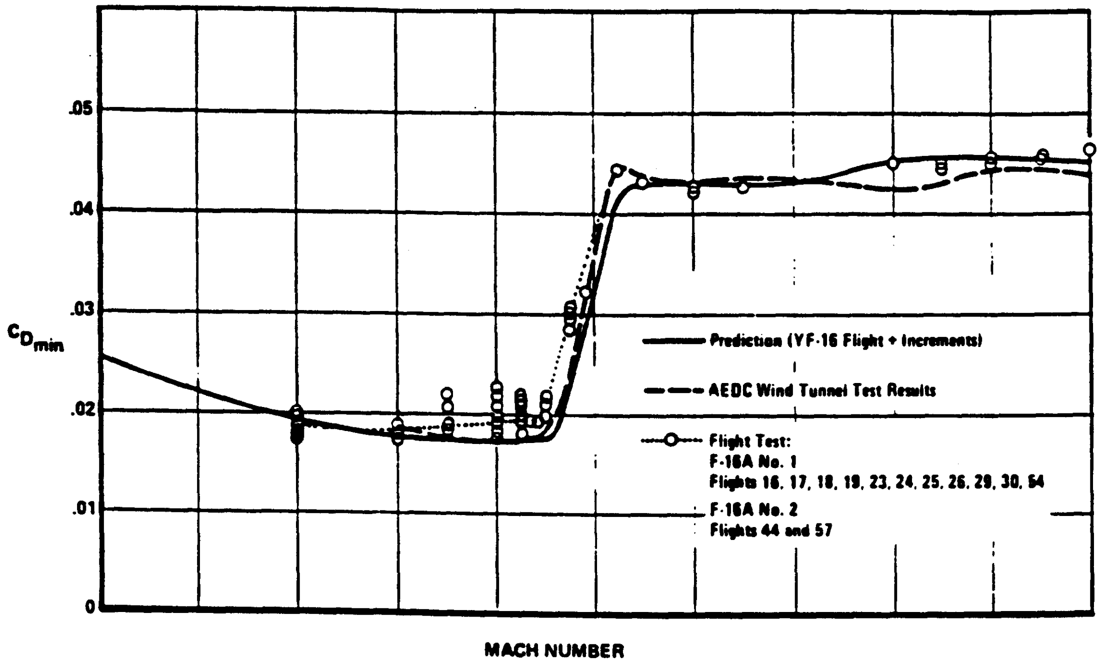

Figure 4-17. *Change in C_{D0} of the F-16 Fighter as a Function of Flight Mach Number [From Webb, 1977, p. 19-11].*

Table 4-4
Specifications for the General Dynamics F-16 Fighter

Parameter	Value
Wing Reference Area (ft^2)	300
Wing Span (ft)	31
Aspect Ratio	3.2
Empty Weight (lb)	15,586
Payload Weight (lb)	1600
Fuel Weight (lb) [Internal Only]	6624
Takeoff Weight (lb)	23,810
Altitude (ft)	35,000
Oswald Span Efficiency Factor	0.70

flight test drag polar provided in Webb (1977, p 19-10). Figure 4-18 plots the results of the calculations. At subsonic Mach numbers, the single F100 engine on the F-16 must provide roughly 2600 lbs of thrust. However, at Mach 1.2, about 7000 lbs of thrust are required, and at Mach 1.6, 12,500 pounds of thrust are required to maintain the aircraft in level flight.

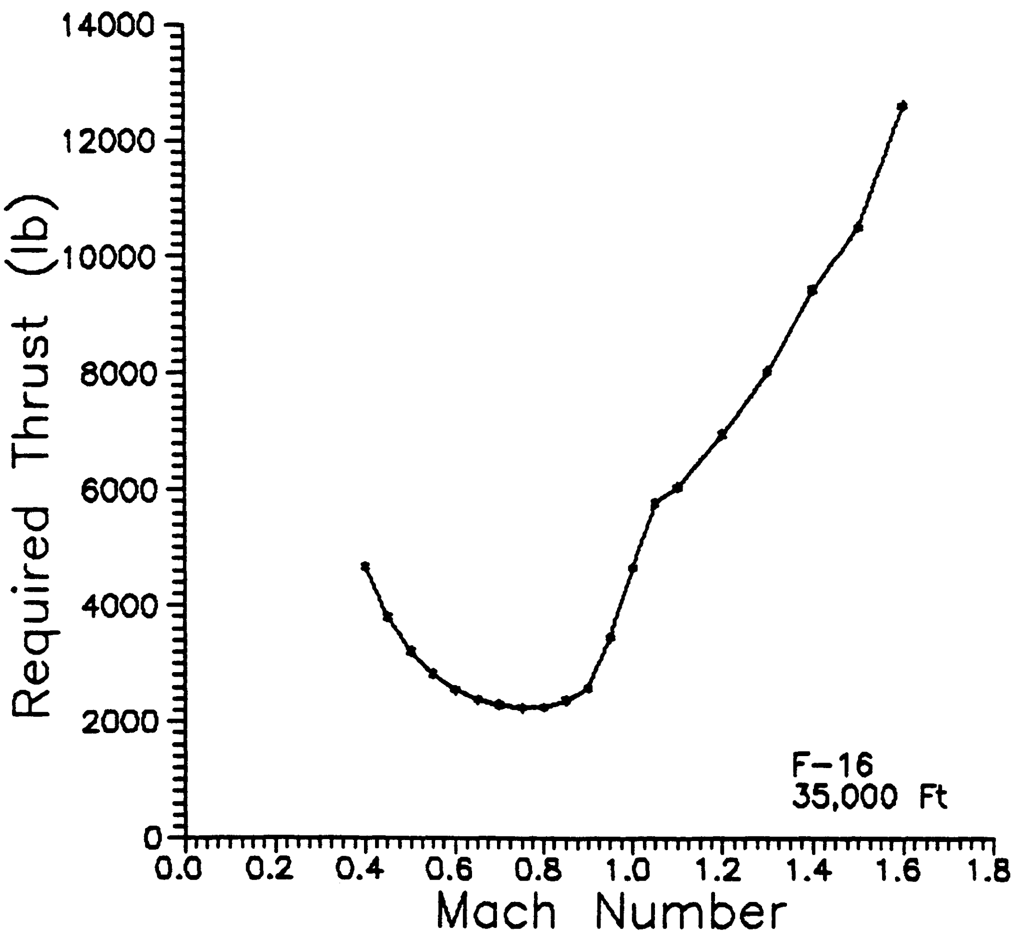

Figure 4-18. *Minimum Thrust Required to Maintain the F-16 in Level Flight at 35,000 Feet.*

Such large thrust requirements are typically met through afterburning. As Figure 4-19 (Nicolai, 1975, p. 14-17) shows, at an altitude of 36,000 feet and a speed of Mach 0.8, the F100 engine without afterburner can supply a maximum of 4,000 pounds of thrust with an SFC just under 0.9 lb/lbt/hr. As shown in Figure 4-20 (Nicolai, 1975, p. 14-13), however, the F100 can generate 13,000 pounds of thrust at Mach 1.2 with its afterburner. At Mach 1.6, the engine can generate 17,000 pounds of thrust. Thus, the F-16 can reach supersonic speeds, but only by using its afterburner. In this mode of operation, SFC is severely degraded.

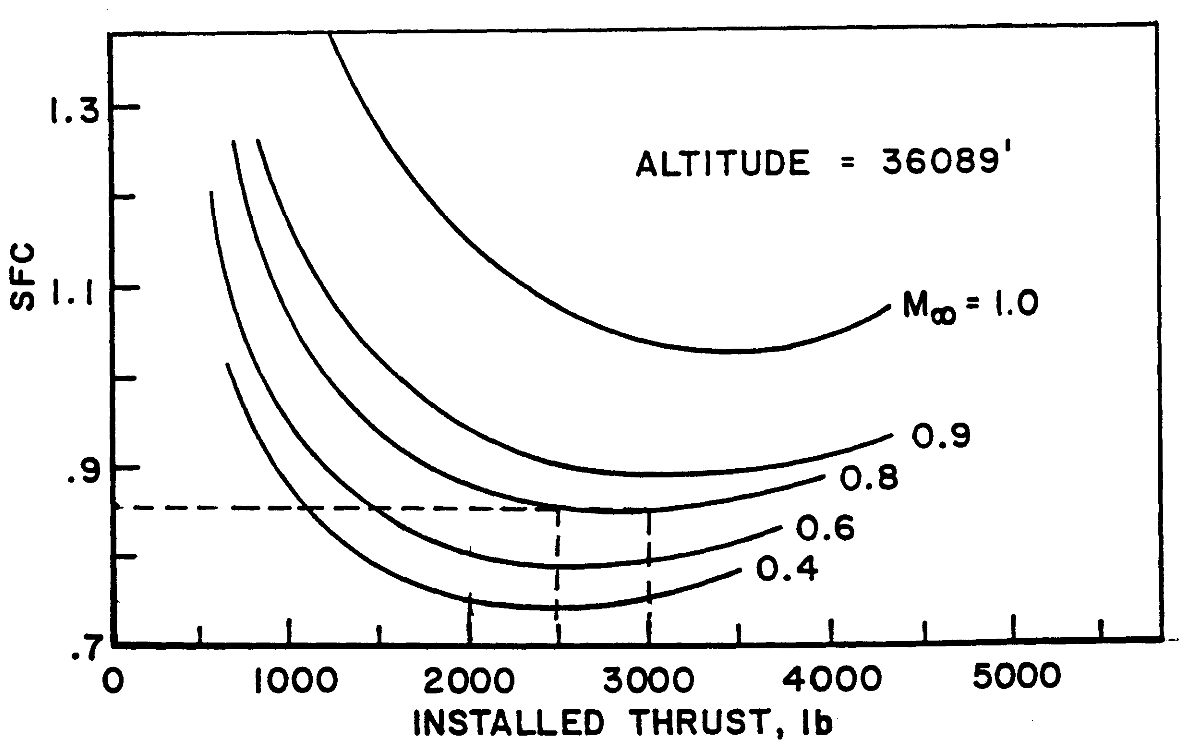

Figure 4-19. Non-afterburning Thrust of the F100 Engine at 36,000 Feet as a Function of Installed Thrust and Mach Number [From Nicolai, 1987, p. 14-17].

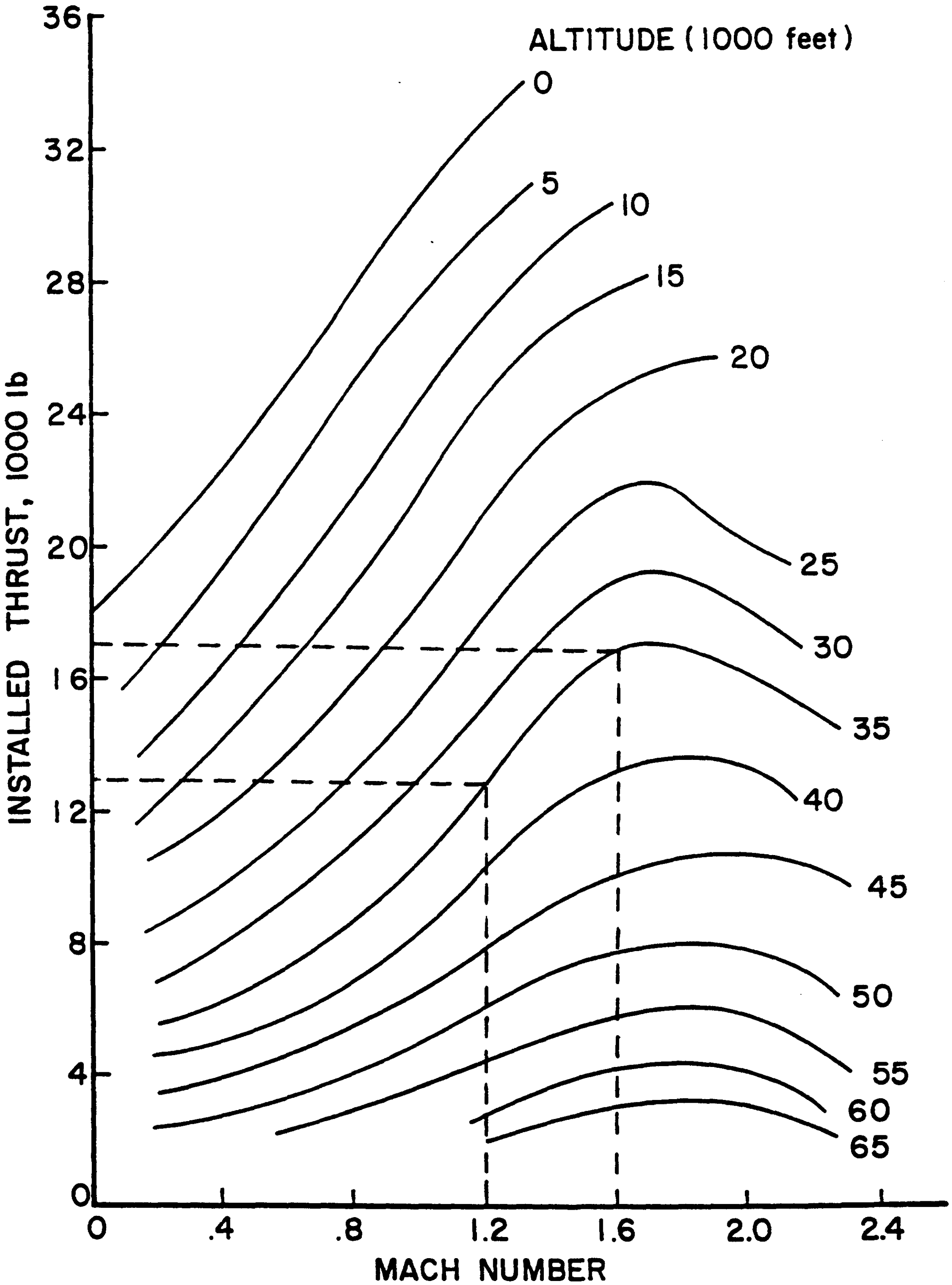

Figure 4-20. *Maximum Afterburning Thrust of the F100 Engine as a Function of Mach Number and Altitude [From Nicolai, 1987, p. 14-13].*

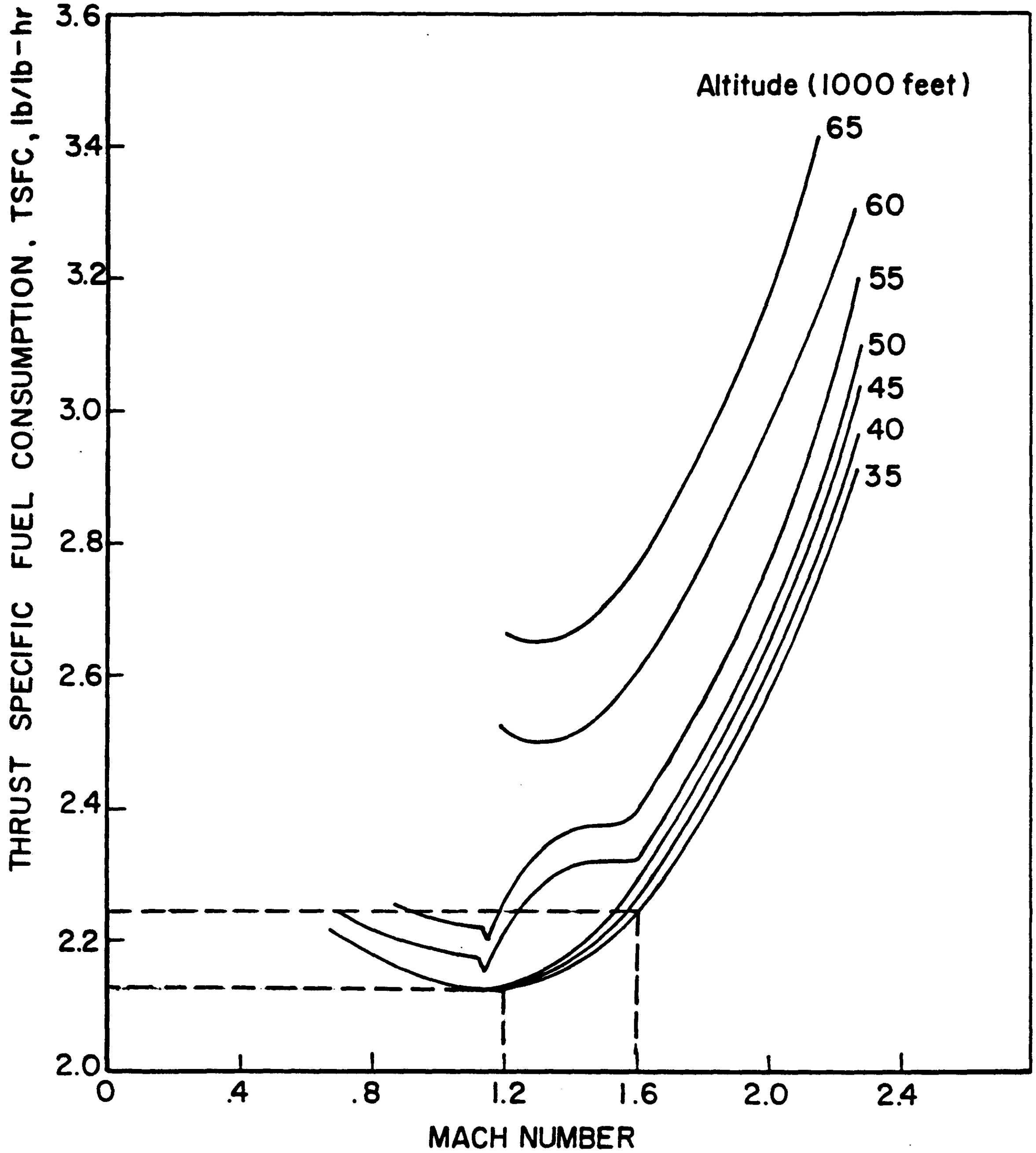

Figure 4-21. Specific Fuel Consumption of the F100 Engine at Maximum Afterburning Thrust [From Nicolai, 1987, p. 14-15].

Figure 4-21 (Nicolai, 1975, p. 14-15) plots the SFC of the F100 with maximum afterburning versus Mach number. At Mach 1.2, SFC is just over 2.1 lb/lbt/hr. At Mach 1.6, SFC is over 2.2 lb/lbt/hr. These figures compare to an SFC of under 0.9 lb/lbt/hr at Mach 0.80. The large increase in SFC implies that the aircraft cannot operate for long periods of time with the afterburner.

Larger fighters such as the F-15 suffer from the same problem. The thrust required to maintain the F-15 in level flight was computed from the data in Table 4-5. Size and weight data were derived from Taylor (1990); the Oswald span efficiency factor was computed using equation 4-11. The C_{D0} for the F-15 with external fuel tanks and armaments was assumed to be 10% higher than the

Table 4-5
Specifications for the McDonnell-Douglas F-15 Fighter

Parameter	Value
Wing Reference Area (ft^2)	608
Wing Span (ft)	42.8
Aspect Ratio	3.0
Empty Weight (lb)	28,600
Payload Weight (lb)	5,300
Fuel Weight (lb)	35,100
Takeoff Weight (lb)	68,000
Altitude (ft)	35,000
Oswald Span Efficiency Factor	0.71
C_{D0} (Subsonic)	0.022
C_{D0} (Supersonic)	0.047

corresponding value for the F-16 due to the larger size of the aircraft and the additional external stores (munitions and fuel tanks) carried on a fully-loaded F-15. Thus, a subsonic C_{D0} of 0.022 and a supersonic C_{D0} of 0.047 were used in the calculations. These values are comparable to the values of C_{D0} presented by Raymer (1989, p. 296) for the F-14. Figure 4-22 shows the result of the thrust calculations for an F-15 at 35,000 feet and at Mach numbers between 0.4 and 1.4. At Mach 0.8 the F-15 requires less than 7000 pounds of thrust for steady flight. This value, as shown in Figure 4-19, is within the range of the two F100 engines used on the aircraft. At Mach numbers of 1.2 and 1.4, 16,000 and 21,000 pounds of thrust are required, respectively. These thrust levels can be achieved only with afterburners, increasing the SFC of the engines dramatically. As shown in Figure 4-23 (Nicolai, 1975, p. 14-19) which plots SFC versus thrust for partial afterburning settings of the F100 at 36,000 feet, the thrust required by the F-15 at these velocities can be provided only at SFCs between 1.7 and 1.8 lb/lbt/hr. According to the Breguet range equation, the increase in SFC compared to the subsonic case will reduce the maximum range of the aircraft. In moving to supersonic velocities, the speed of the aircraft about doubles, but the lift-to-drag ratio decreases by a factor of two, negating the effect of increased velocity. Thus, rise in SFC will be reflected in a corresponding decrease in maximum range.

The F-15 analysis is interesting because it sheds light on requirements for the Air Force Advanced Tactical Fighter (ATF) aircraft. Military requirements for this aircraft state that the ATF should be able to maintain supersonic cruise capability ("supercruise") without the use of afterburners. This requirement will greatly

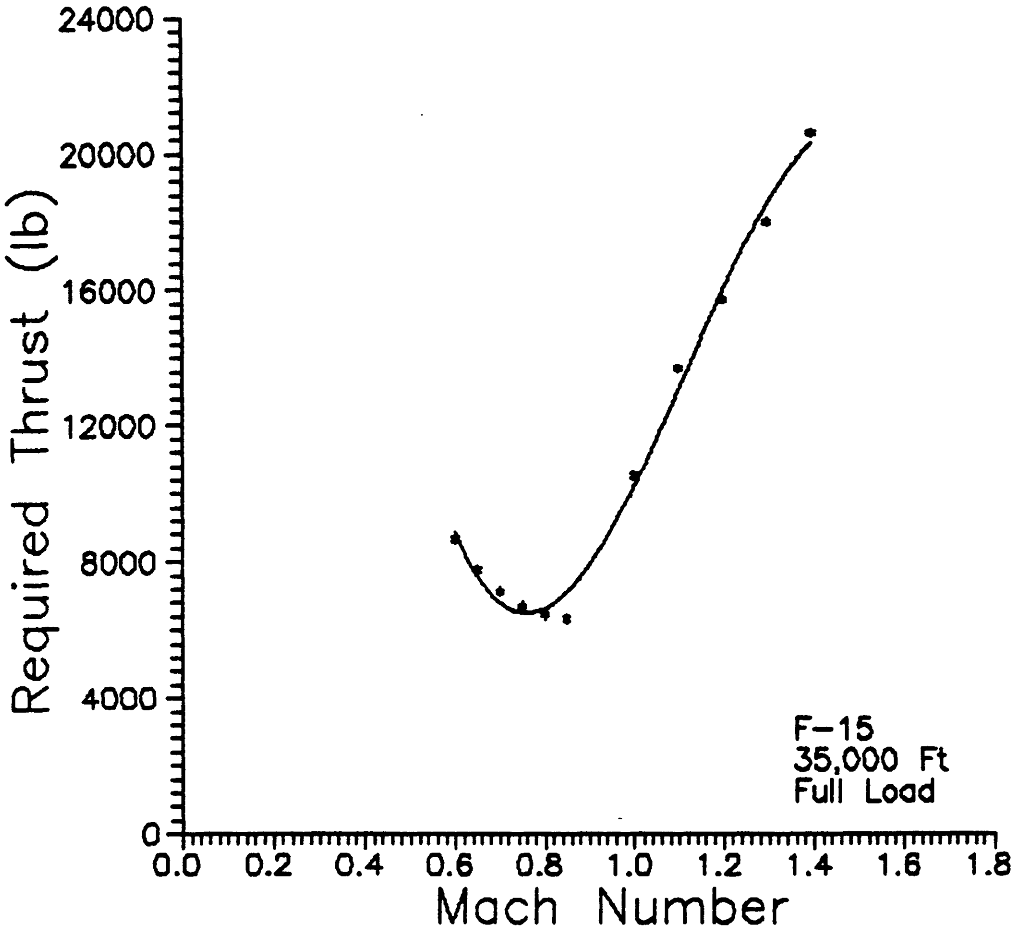

Figure 4-22. *Minimum Thrust Required to Maintain a Fully-Loaded F-15 in Level Flight at 35,000 Feet Versus Flight Number.*

increase the supersonic range of the ATF because the SFC of the engine will be below the afterburning SFC of the F100 engine. The ATF is similar to the F-15 in terms of size and weight. Therefore, the supercruise requirement will necessitate the development of engines that can produce 11,000 pounds of thrust or more apiece at altitude without afterburning. At the same time, these engines must meet size and weight constraints similar to those of the F100 engine. Hence, the ATF engine will need to be designed for high specific thrust. Methods for achieving higher specific thrust will be examined in Chapter V.

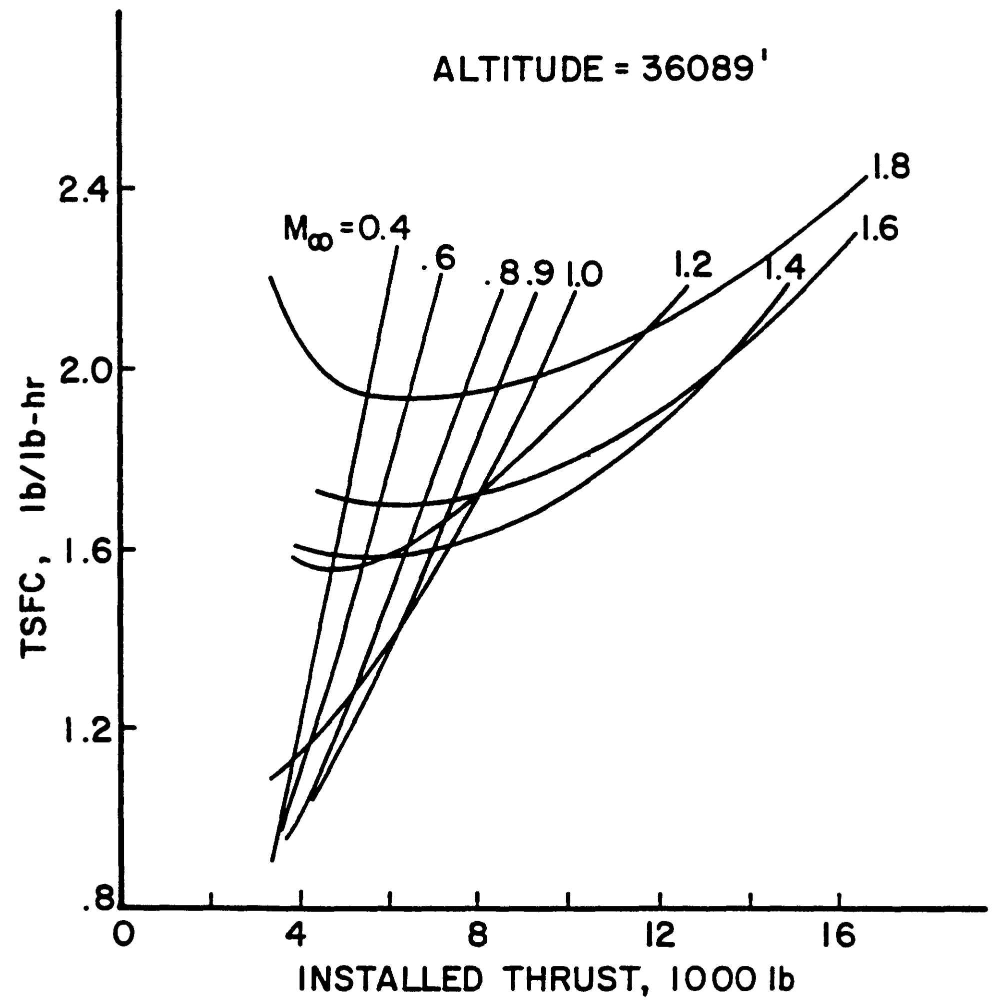

Figure 4-23. Specific Fuel Consumption of the F100 Engine at 36,000 Feet for Partial Afterburning Power Settings [From Nicolai, 1987, p. 14-19].

Fighter engines are subject to additional design constraints as well. In addition to providing high thrust, fighter engines must meet strict size and weight restrictions in order to be properly integrated onto their airframe. Fighter aircraft have operating weights on the order of 30,000-60,000 lbs; engine weight represents a significant portion of this total. The F100 engine and the upgraded F117 engine weigh between 3000 and 3700 pounds. Thus, these engines comprise approximately 10% of the operational weight of the F-15 and F-16. Fuel comprises another 25 to 50% of maximum takeoff weight. Further increases in engine or fuel weight could seriously degrade aircraft performance, so increases in thrust must be gained without corresponding increases in engine weight. Requirements for stealth and supersonic capability further constrain fighter engine size as they do bomber engine size. As a result, military fighter engines are rated in terms of thrust-to-weight ratios and specific thrust. Both of these criteria refer to the ability of an engine to generate high thrust with low cross-sectional area and low weight.

These two constraints, high specific thrust and low weight drive fighter engine design toward low-bypass ratio turbofan engines. Fighter aircraft could be powered by higher bypass ratio engines to obtain better fuel efficiency and range, but such benefits would be greatly outweighed by the increased weight and drag. As fighter aircraft can be deployed from aircraft carriers and refueled in-flight, the advantages of greater range pale in comparison to the enhanced performance provided by lower bypass ratio engines.

D. Summary

The above discussion indicates the general trends that the commercial and military requirements for jet aircraft engines can be expected to follow. Commercial development will concentrate on improving the SFC of high-bypass turbofan engines and on the continued development of propfans. The goal of both these endeavors will be to decrease the direct operating costs of airlines by reducing the amount of fuel burned during flight.

Military interests will concentrate on the development of low-bypass ratio turbofans. These engines present a reasonable compromise between the thrust required from fighter and bomber engines and the small cross-sectional area required for stealth, low-drag, and airframe integration. The primary goal of military engine development will more likely focus on increases in specific thrust than on reductions in SFC.

Military interest in propfan technology will be limited. First, the propfan engines envisioned today cannot produce the thrust required to power large military bombers or to accelerate fighter aircraft to supersonic velocities. The propfan engines currently under development by GE and Pratt & Whitney/Allison are in the 25,000 pound static sea-level thrust class. Increases in thrust can be achieved only by increasing the size of the engine core and the size of the rotor blades. Moreover, the exposed blades of these engines negate attempts to design stealth into the aircraft. Propfan blades are both large and unducted.

These trends will establish the basis from which technology transfer and commercialization can occur in the U.S. jet aircraft engine industry. The next chapter will attempt to investigate the technical means by which the military will improve its engines and evaluate the ability of such improvements to lower the SFC of commercial engines.

CHAPTER V

PROSPECTS FOR FUTURE COMMERCIALIZATION AND TECHNOLOGY TRANSFER

The requirements outlined in Chapter IV for future commercial and military aircraft and engines determine the constraints on technological innovation in the jet engine industry; however, they do not necessarily determine the specific technologies to be developed. For this reason, the analysis of future prospects for commercialization and technology transfer in the jet engine industry must include consideration of the technologies likely to be incorporated into future engines. This chapter analyzes research areas likely to generate technology for future military and commercial engines. In doing so, it makes no attempt to project the likelihood of particular technologies being developed over time or the cost associated with such development; rather it uses insight gained from ideal cycle analysis to investigate areas of technical advancement capable of meeting the future requirements for commercial and military jet aircraft engines. This chapter then attempts to assess the degree of commonality between likely military and commercial innovations with an eye toward technology transfer considerations.

This chapter is divided into three sections. The first uses ideal cycle analysis to examine the technological innovations most likely to be pursued in meeting the military's goals for future fighter- and bomber-class engines. The effects of turbine inlet temperature, compression ratio, bypass ratio, and component efficiencies upon specific thrust and specific fuel consumption will be demonstrated.

Commercial engines are analyzed in the next section in order to investigate the types of innovation likely to bring about future reductions in SFC. The degree to which the military research will apply to commercial engines will be also discussed, and areas in which commercial and military research appear to be diverging will be identified. In both these sections, current research programs will be identified and described in order to demonstrate the goals of engine research. Finally, several conclusions will be drawn regarding the future of technology transfer and commercialization within the jet engine industry.

A. Research Directions for Military Engines

Efforts to improve the performance of military jet engines may pursue a number of paths. As was demonstrated in Chapter IV, the primary goal of these efforts will be to develop technologies capable of increasing the specific thrust and the thrust-to-weight ratios of low bypass ratio turbofan engines. To a lesser degree research on military engines will focus on lowering the SFC of these engines, specifically for long-range bombers, or on maintaining present levels of SFC while increasing specific thrust.

Recent efforts in the development of military engines have focused upon the Advanced Tactical Fighter (ATF) engine. The ATF itself is being pursued as a replacement for the Air Force's F-15 fighter. Both Pratt & Whitney and GE participated in the engine competition with Pratt recently being declared the winner. A major goal of the ATF engine program was the development of an engine capable of propelling the ATF at speeds of Mach 1.4-1.6 without afterburning.

Such requirements dictated an engine with a thrust-to-weight ratio of approximately 10 to 1 and a maximum static thrust of 35,000 pounds compared to the 25,000 pounds generated by the F100 engine used on the F-15 (Dornheim, 1991, p. 44). Key factors in engine design intended to achieve these thrust and weight requirements were increased turbine inlet temperatures and reduced bypass ratios.

Development of post-ATF engine technologies is being pursued under the Department of Defense's Integrated High-Performance Turbine Engine Technology Program (IHPTET). IHPTET is being jointly sponsored on a cost-sharing basis with industry by a number of agencies including the U.S. Air Force, Army, and Navy, NASA, and the Defense Advanced Research Projects Agency (DARPA). The program is designed to develop technology to the point at which it can be incorporated into demonstration/validation or full-scale development programs, but IHPTET is not intended to develop specific engines.

In general terms, the goal of the IHPTET initiative is to improve key engine performance parameters such as thrust and SFC by a factor of two. Turbojet, turbofan, and turboshaft/turboprop technologies are all addressed by the program. Individual goals for the different engine types goals are to be met through a sequence of three phases ending in the year 2003. The first two phases are planned to end in 1991 and 1997, respectively, with technology developed during these phases being transitioned into current production engines. Table 5-1 summarizes some of the goals for the IHPTET program (Interavia, 1989, p. 1114). All performance goals are referenced to current state-of-the-art engines such as the

Table 5-1
Primary Goals of IHPTET Program

Parameter	Phase I	Phase II	Phase III
Turbojet/Turbofan			
Thrust:Weight Ratio	+30%	+60%	+100%
Compressor Inlet Temp	+55K	+170K	+255K
Maximum Temperature	+170K	+340K	+510K
Turboshaft/Turboprop			
SFC	-20%	-30%	-40%
Power:Weight Ratio	+40%	+80%	+120%
Maximum Temperature	+170K	+340K	+555K
Expendable TJ/TF			
SFC	-20%	-30%	-40%
Specific Thrust	+35%	+70%	+100%
Maximum Temperature	+275K	+510K	+780K

[From: *Interavia*, 1989, p. 1113]

ATF engine or T800 turboshaft engine. As shown, IHPTET intends to double the thrust-to- weight ratios of turbojet and turbofan engines by 2003. While part of this improvement will derive from increases in operating temperatures as noted in the table, the remainder will derive from lighter weight materials and components. Work in the turbojet/turbofan area is of most interest in terms of technology transfer to commercial airliner engines. While the advances in turboshaft/turboprop work may have some applicability to commercial engines, the technology for turboprop engines developed through IHPTET would most likely be geared toward smaller engines than would be used on commercial airliners (Interavia, November 1989, p. 1114).

This section of the report uses ideal cycle analysis to investigate the types of innovations likely to produce engines with higher specific thrust. The equations used in this analysis are not identical to those defined in Chapter II; rather, these equations include non-ideal effects of individual components. The equations for describing the behavior of such components are described in Mattingly (1989). Unless otherwise specified, the performance curves presented in this chapter were developed using the ONX and OFFX programs developed by Mattingly to accompany his text.

The performance of a turbofan engine at its design point is a function of four primary design variables: turbine inlet temperature, overall compression ratio, fan pressure ratio, and bypass ratio. In addition, component efficiencies--the turbine and compressor polytropic efficiencies, in particular--also influence the behavior of the engine. The following analysis examines the effect of these parameters on overall engine performance. Changes in performance are measured in comparison to the performance of a base engine described by the parameters in Table 5-2. This engine is a low-bypass-ratio turbofan representative of current fighter class engines such as the F110 engine used on the F-15 and F-16 fighters. A modified version of the F110, designated the F118, powers the B-2 bomber, so subsonic assessment of this engine is also indicative of trends in bomber engine development.

Table 5-2

Parameters for Base Case Military Engine

Parameter	Value
Bypass Ratio	0.80
Maximum Turbine Inlet Temp (°R)	2900
Overall Compression Ratio	30
Polytropic Efficiency: Turbine	0.90
Polytropic Efficiency: Compressor	0.90
Cooling Air Flow (Each Spool)	5%

1. Turbine Inlet Temperature:

Military research will most likely pursue development of new materials and cooling techniques in order to increase the maximum turbine inlet temperature of jet engines. The specific thrust of an engine is a strong function of turbine inlet temperature; increases in the maximum allowable turbine inlet temperature allow more fuel to be burned during combustion, transferring more energy to the core airstream and improving thrust. The thermal efficiency of the engine cycle is also increased at higher turbine inlet temperatures, though potentially at the expense of propulsive efficiency and SFC. For military engines, however, the gains in specific thrust are typically seen as outweighing the rise in SFC. This is especially true in the case of fighter engines. A large increase in specific thrust can allow fighter aircraft to cruise at supersonic speeds without afterburning and thereby increase their fuel efficiency compared to current engines which must use afterburning to develop supersonic thrust levels.

The effect of increased turbine inlet temperature (TIT) on specific thrust is demonstrated in Figure 5-1. This graph shows the increase in specific thrust for the base engine at an altitude of 35,000 feet and a speed of Mach 0.8 as maximum TIT is increased from 2900°R to 3800°R. The overall compression ratio is held constant at 30; fan pressure ratio is also held constant at 3. As the curve shows, specific thrust varies almost linearly with TIT over the range examined. By increasing TIT from 2900 to 3800°R, the specific thrust of the engine increases 28%, from 51.1 lbt/lbm/s to 65.5 lbt/lbm/s. This translates into an increase of 3% in specific thrust for each 100 degree Rankine increase in temperature, assuming a linear relationship over the range examined. Greater increases in specific thrust could be gained by changing other design factors (such as fan and compressor pressure ratios) as the TIT increases.

The large increase in specific thrust results from the increase in the velocity at which the core stream exits the engine. By increasing the maximum allowable temperature of the turbine, more fuel can be combusted in the burner and thus more thermal energy can be released during the combustion process. As this thermal energy is imparted to the airflow in the form of mechanical energy, the velocity of the core airflow will increase. In fact, over the interval shown in Figure 5-1, the ratio of the core exhaust velocity to the inlet airflow velocity increases from approximately 2.5 to 3.0. From the expression for specific thrust derived in Chapter II, it can be seen that this increase in exhaust to inlet velocity ratio translates into an increase in specific thrust.

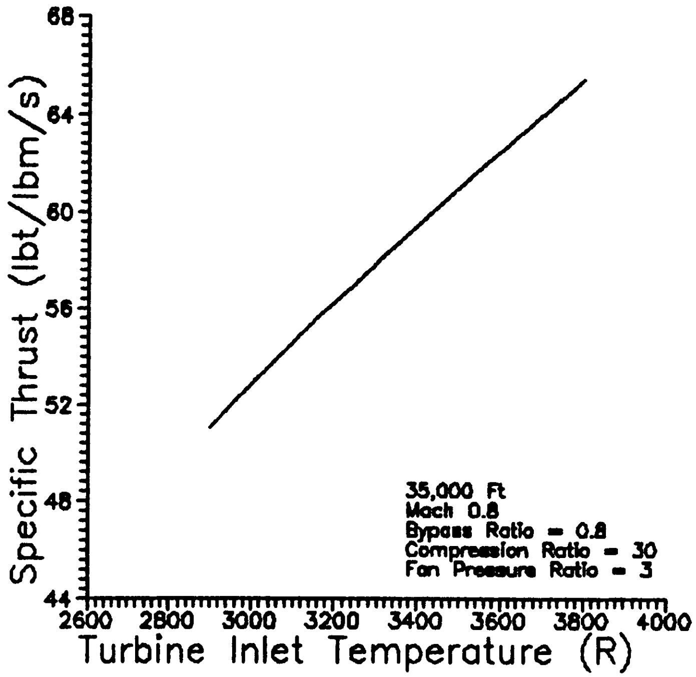

Figure 5-1

Influence of Turbine Inlet Temperature on the Specific Thrust of a Low Bypass Ratio Turbofan at Mach 0.80.

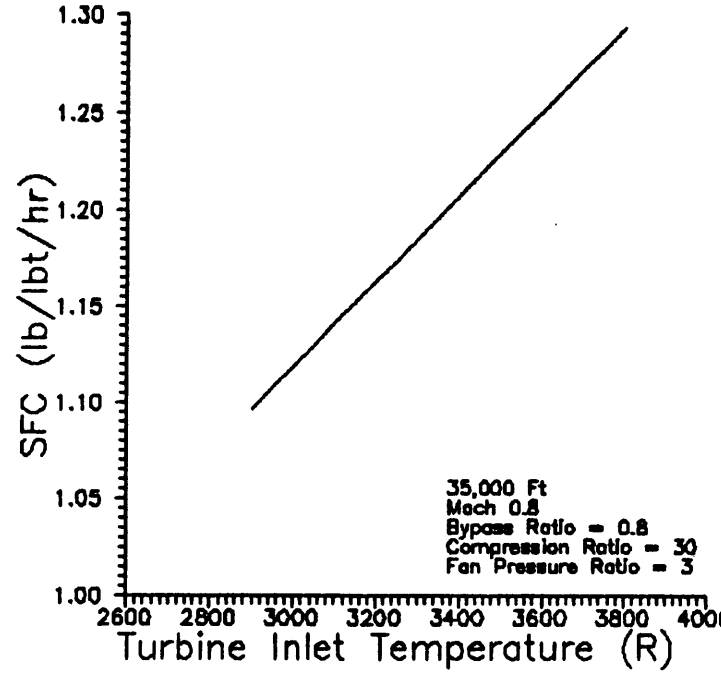

Figure 5-2

Influence of Turbine Inlet Temperature on the SFC of a Low Bypass Ratio Turbofan at Mach 0.80.

The increase in exhaust velocity simultaneously decreases the propulsive efficiency of the engine. Thus, despite the increase in thermal efficiency, the overall efficiency of the engine and its SFC decline. This effect is demonstrated in Figure 5-2 which plots SFC versus TIT for the base engine. This curve was computed by varying the TIT between 2900 and 3800°R while holding all other design variables constant. The graph shows that SFC increases from 1.1 lb/lb/hr to 1.3 lb/lb/hr as TIT increases over this interval. As with specific thrust, the relationship is nearly linear over the range examined. This relationship assumes that other design parameters are held constant. As will be demonstrated later in the text, the effects of increased TIT upon SFC can be compensated for by changing other design parameters such as bypass ratio or compression ratio.

The increase in SFC with TIT implies that a tradeoff must be made between specific thrust and SFC in the design of an engine unless other design changes are made in the engine. In order to achieve higher specific thrust, the turbine entry temperature of the engine can be increased; however, the engine will then have a higher SFC. This relationship is summarized in Figure 5-3 which plots SFC versus specific thrust using the figures computed in Figures 5-1 and 5-2. Each point on the graph represents a different turbine inlet temperature. For increasing values of TIT, specific thrust increases as does SFC. Thus, engine designers must judiciously select the turbine inlet temperature that best suits the performance requirements of the aircraft.

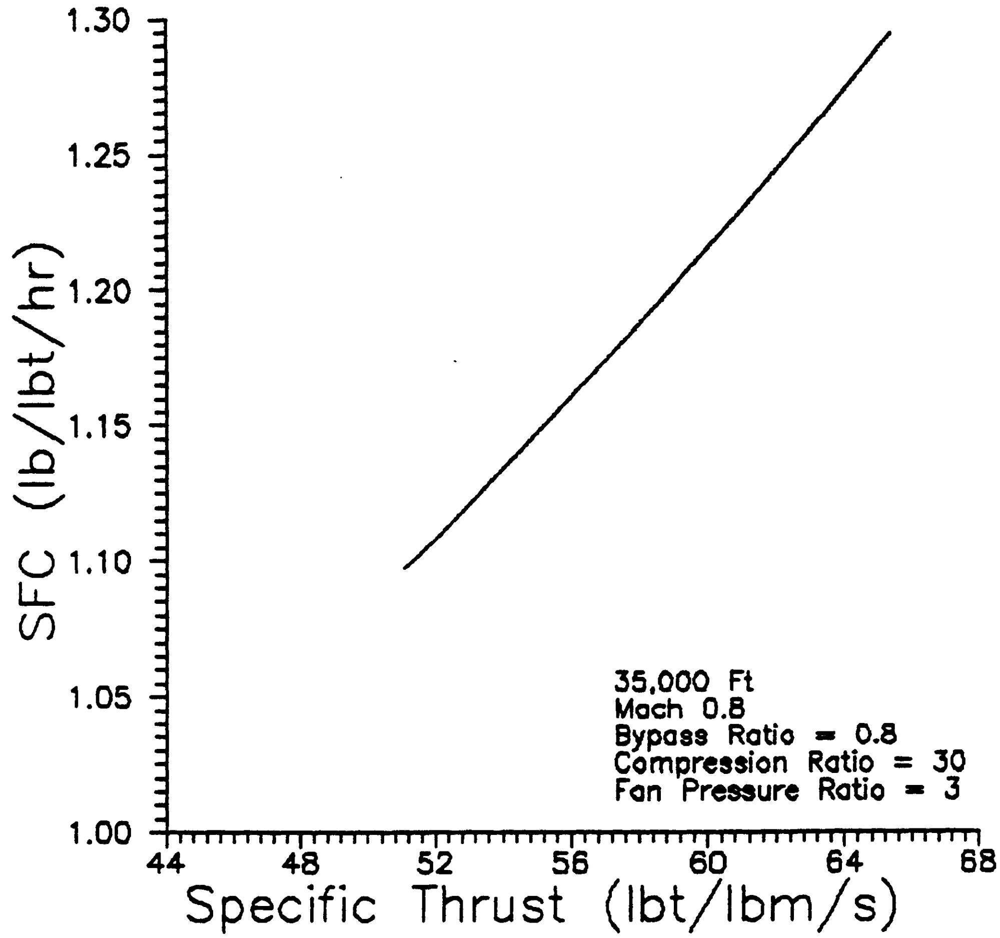

Figure 5-3. *Tradeoff Between Specific Thrust and Specific Fuel Consumption As Turbine Inlet Temperature is Increased.*

For military aircraft, specific thrust is a key design parameter. In military fighters especially, the increase in SFC with specific thrust is an acceptable design tradeoff because the increase in thrust can allow continuous flight at Mach numbers above 1.5 without afterburners. Current fighters with uprated engines can cruise slightly above Mach 1, but only under certain circumstances (Dornheim, 1991, p. 44). As was demonstrated in Chapter IV, the engine thrust requirements for supersonic flight are extremely high. Engine thrust declines significantly at higher Mach numbers. Thus, engines used on supersonic aircraft must be designed with high specific thrust. Increased turbine inlet temperature can provide part of this thrust requirement. Figure 5-4 plots the change in specific thrust versus TIT for an engine with a design point of 35,000 feet and Mach 1.6. As for the subsonic case, specific thrust increases linearly with TIT. By comparing this figure with Figure 5-1, it can be seen that the engine designed for supersonic flight with a TIT of 3800°R has almost the same specific thrust as the engine designed for subsonic flight with a TIT of 2900°R. Further increases in turbine inlet temperature could allow additional gains in specific thrust sufficient to sustain supersonic cruise. SFC will increase with TIT as shown in Figure 5-5; however, these SFC levels are substantially lower than those for an afterburning engine and would result in efficiency improvements for the engine compared to current afterburning engines.

Subsonic aircraft can also benefit from increases in TIT. The higher specific thrust of the engine allows the engine to generate a given thrust level from a smaller airflow. Thus, the size of the engine can be reduced without sacrificing aircraft performance. On the contrary, aircraft performance will improve as the smaller engine will be lighter and generate less drag. The increase in SFC caused by the higher TIT may be offset by carrying additional fuel or by other design changes that can lower SFC such as increased bypass ratio or compression ratio. These will be highlighted in subsequent discussion.

The benefits of increased turbine inlet temperature for military engines imply that much research will continue to be directed in this area. The primary focus of this

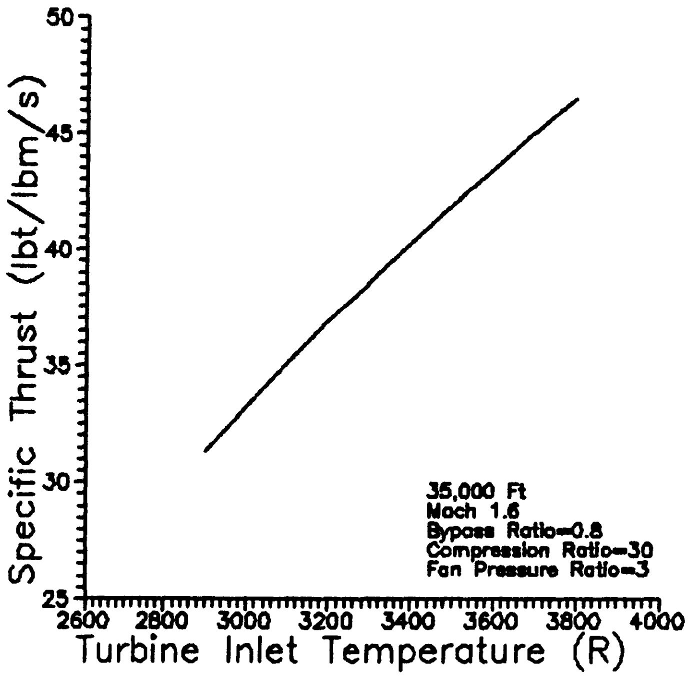

Figure 5-4

Influence of Turbine Inlet Temperature on the Specific Thrust of a Low Bypass Ratio Turbofan at Mach 1.6.

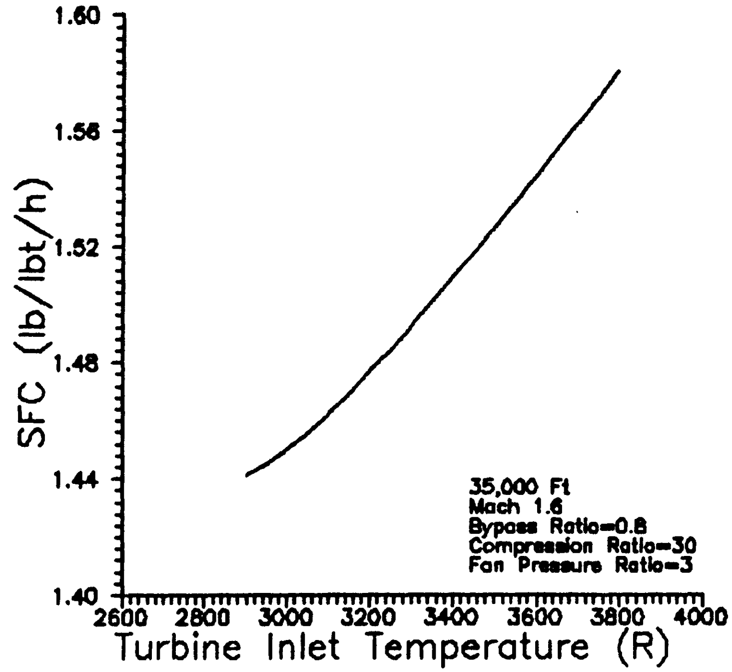

Figure 5-5

Influence of Turbine Inlet Temperature on the SFC of a Low Bypass Ratio Turbofan at Mach 1.6.

research will be to develop new materials for turbine construction. Several such materials are being developed under the auspices of IHPTET. Inter-metallic materials are expected to be developed in Phase I of the program. These materials such as nickel-aluminides and titanium-aluminides retain the heat-resistant qualities of their base metals, but are lighter-weight because of their aluminum content. Nickel aluminides are only half the weight of nickel. Metal matrix composites (MMC) are expected to be developed during Phase II of IHPTET, and ceramics such as silicon nitride will probably be introduced into Phase III engines (Interavia, 1989, p. 1114).

Some of these Phase I materials have already been introduced into the design of the ATF engine. This engine operates with a higher turbine inlet temperature than its predecessors. The most recent upgrade of the F100 engine, the PW 220-229 operates with a maximum turbine inlet temperature of 2595 degrees Fahrenheit; the Pratt & Whitney YF119 engine (recently selected as the winner of the ATF engine competition) is estimated to operate at temperatures just below 3200 degrees Fahrenheit (Gal-Or, 1990, p. 206).

2. Cooling Requirements:

Advances in turbine materials provide an additional benefit to aircraft engines as they allow reductions in the cooling air requirements for turbofan engines. In current turbofans, more than 10% of the total core airflow may be diverted into the cooling system to cool the turbine blades. Such cooling is required to allow the turbine to operate at higher temperatures than its materials can otherwise withstand. By pumping cool air into hollow turbine blades, some of the heat can be removed from blades, preventing them from overheating and failing.

Reductions in turbine cooling requirements translate into increases in specific thrust as more core air can be accelerated by the combustion process. The figures calculated in the previous section assumed that 10% of the core airflow was diverted for cooling the high and low pressure turbine spools. Five percent of the air was assumed to be diverted to each spool. The effect of reducing these requirements while maintaining a constant turbine inlet temperature of 2900°R and a constant pressure ratio of 30 is shown in Figure 5-6. With a cooling air requirement of 5% for each spool, the specific thrust of the engine is 51.3 lbt/lbm/s; with no cooling air requirements, the specific thrust increases to almost 55 lbt/lbm/s, a five percent gain in specific thrust.

Unless accounted for by other design changes, reductions in cooling air can actually cause an increase in SFC. As the cooling airflow is reduced, the mass of air flowing through the core and being combusted increases accordingly. The velocity at which the core airflow is exhausted from the engine must also increase by conservation of mass considerations. Because propulsive efficiency is inversely proportional to the velocity of the core flow, the propulsive efficiency of the engine must decrease. Unless the increase in thermal efficiency is sufficient to overcome this deficit, SFC will also be reduced. However, fuel efficiency can be partially regained without sacrificing the improvement in specific thrust by increasing the bypass ratio of the engine or by increasing compression ratio[1].

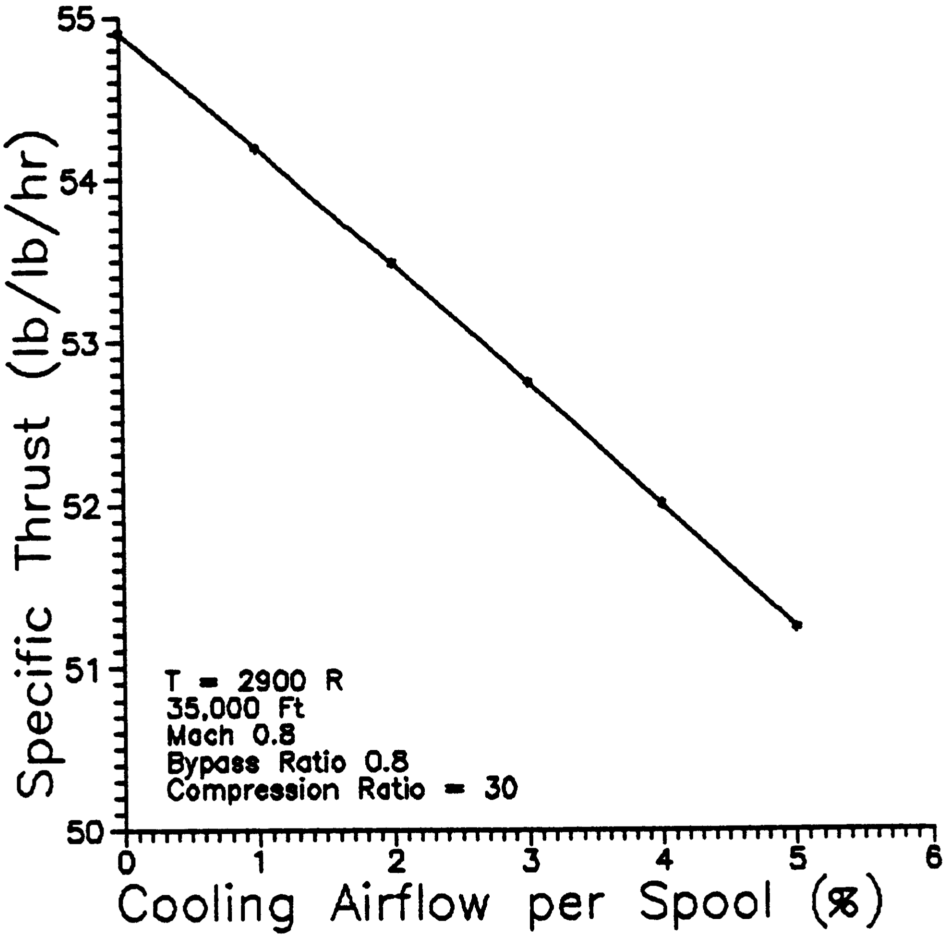

Figure 5-6. *Influence of Cooling Airflow Requirements on the Specific Thrust of a Turbofan Engine with a Bypass Ratio of 0.80.*

[1]The increase in compression ratio does not improve SFC by decreasing the velocity of the core airflow, but by improving the thermal efficiency of the engine cycle.

3. Compressor Design:

Military engines can also benefit from advances in compressor design. These benefits can take the form of increased overall compression ratios[2] and lower compressor weight brought about by increases in compressor stage pressure ratios. The application of this research to subsonic and supersonic aircraft, though, may differ.

The desired compression ratio for an engine designed for supersonic flight differs from that of an engine designed for subsonic flight due to the effects of increased ram pressure. Ram pressure refers to the total pressure of the airflow at the entrance to the engine inlet. As flight velocity increases, the total pressure of the airflow at the entrance to the inlet increases in accordance with the definition of total pressure presented in Chapter II. The total temperature of the airflow at the inlet also increases with flight velocity in accordance with the adiabatic temperature-pressure relation, $T = P^{\gamma/(\gamma - 1)}$. For given compressor pressure ratio, therefore, the temperature of air at the exit of the compressor will be higher for an engine flying at supersonic speeds than for an aircraft flying at subsonic speeds. As the maximum allowable temperature of the gas at the exit of the combustor is limited by the thermal properties of the turbine inlet materials, the increased temperature at the entrance to the combustor reduces the amount of heating that can occur in the combustor and hence limits the net thrust of the engine.

[2]Overall compression ratio (or overall pressure ratio) is defined as the product of the fan pressure ratio and the compressor pressure ratio. It is therefore the ratio of the total pressure of the core airstream at the entrance of the combustor to the total pressure at the exit of the engine inlet.

Due to the ram effect, the optimal compression ratio for an engine designed for supersonic flight is less than that for a subsonic engine. This effect can be seen in Figure 5-7 which plots specific thrust versus Mach number for three different compression ratios: 10, 20, and 30. The engine in this case is assumed to be a mixed exhaust turbofan engine in which fan pressure ratio is optimized for maximum specific thrust[3]. TIT is held constant at 2900°. Below Mach 1, the engine generates maximum specific thrust at higher compression ratios; at speeds above Mach 1, however, the engine generates maximum specific thrust at lower compression ratios. Figure 5-8 plots SFC versus Mach number for the same engine analyzed above. For velocities below Mach 1.8, the SFC of this engine is lowest with a compression ratio of 30. The steep rise in SFC at Mach numbers above 1.8 results from the low specific thrust generated at these speeds. In actuality, this engine would not be run at such high speeds, so SFC can be considered lower at higher pressure ratios regardless of flight velocity. As these results indicate, the design of engines for supersonic cruise will not generate requirements for increased compression ratios as high as those for subsonic engines.

The optimum pressure ratio for subsonic and supersonic engines is actually a function of turbine inlet temperature. Increases in maximum TIT increase the

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[3]For a mixed exhaust turbofan, the core and bypass streams are assumed to be exhausted from a single nozzle as is typical of most military engines. For optimal engine performance, the total pressures of the core and bypass stream mass flows should be equal at the entrance to the mixer. Given an overall pressure ratio, this requirement uniquely determines the fan pressure ratio required to meet this condition. Equations for calculating this fan pressure ratio are derived in Mattingly (1987, p. 111).

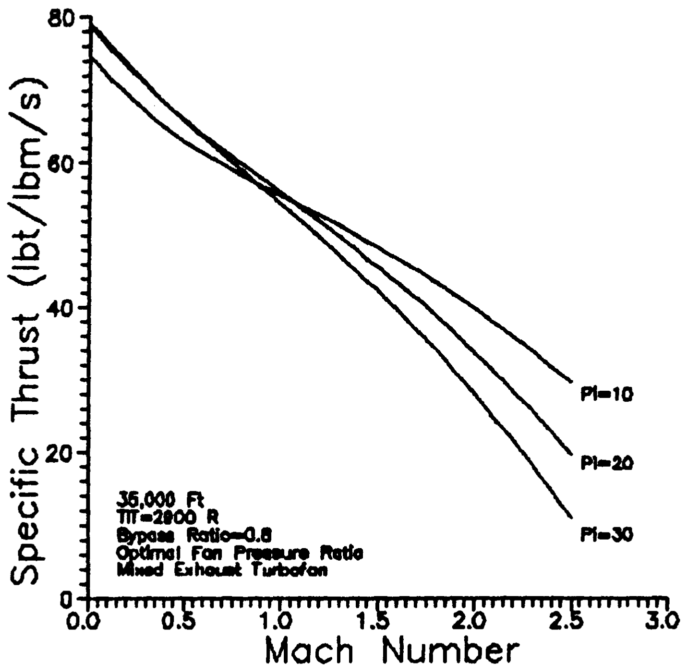

Figure 5-7

Comparison of the Specific Thrust of Low Bypass Turbofan Engines With Different Overall Compression Ratios.

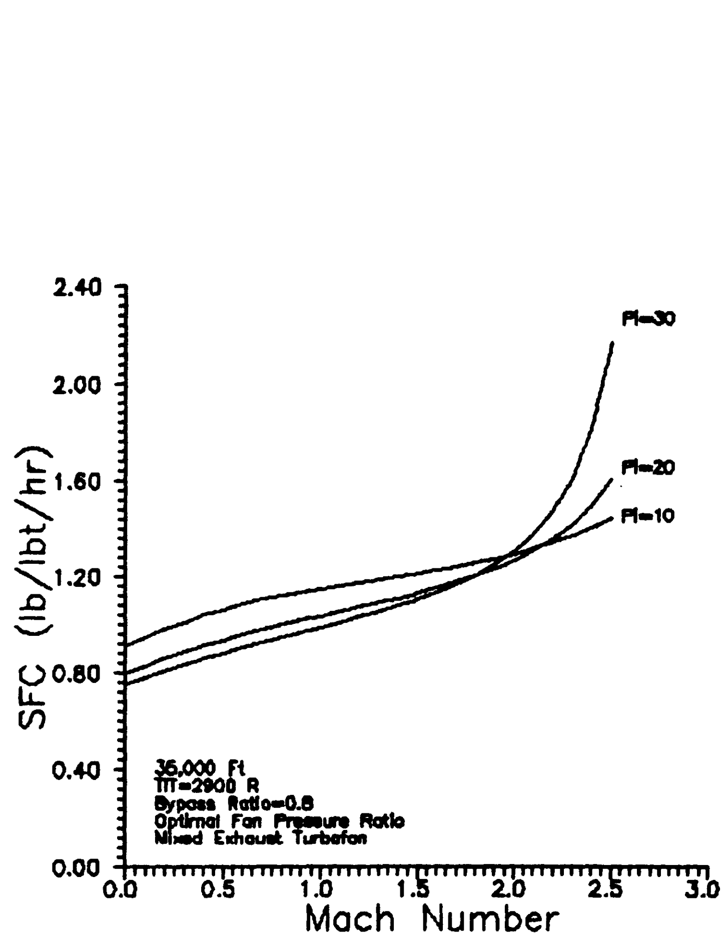

Figure 5-8

Comparison of the Specific Fuel Consumption of Low Bypass Ratio Turbofan Engines With Different Overall Compression Ratios.

compression ratio at which specific thrust is optimized. Figures 5-9 and 5-10 demonstrate the relationship between TIT and compression ratio for subsonic and supersonic engine designs, respectively. These figures plot specific thrust versus compression ratio for four different turbine inlet temperatures; Figure 5-9 shows the result for an engine designed to operate at Mach 0.8, and Figure 5- 10 plots the result for an engine designed to operate at Mach 1.6. In both cases, the engine is assumed to have mixed exhausts, and the fan pressure ratio is selected to maximize specific thrust at each overall pressure ratio examined. These graphs demonstrate that an optimal pressure ratio exists for maximizing the specific thrust of subsonic and supersonic engines and that this optimal pressure ratio increases with turbine inlet temperature. For the subsonic case, optimal pressure ratio increases from 18 to 32 as TIT increases from 2900 to 3800 degrees. For the supersonic case the increase is smaller; the optimal compression ratio increases from 8 to 12 as TIT increases from 2900 to 3800 degrees. Moreover, these graphs demonstrate that specific thrust is only a weak function of compression ratio. At each TIT examined, compression ratio can be increased past the optimal point with only a minor change in specific thrust.

Furthermore, as this analysis demonstrates, the optimal compression ratio for supersonic engines is lower than that for subsonic engines. Thus, should military engines be developed for supersonic cruise capability, increases in overall compression ratio may be pursued only as turbine inlet temperatures are increased. The emphasis on supersonic cruise requirements may obviate advances in overall compression ratio.

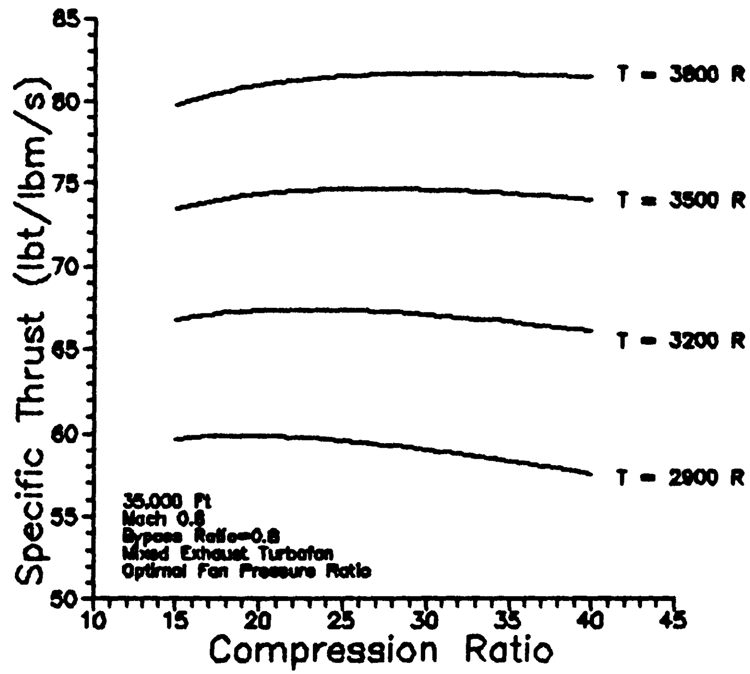

Figure 5-9

Variation in the Specific Thrust of a Low Bypass Ratio Turbofan With Compression Ratio and Turbine Inlet Temperature at Mach 0.80.

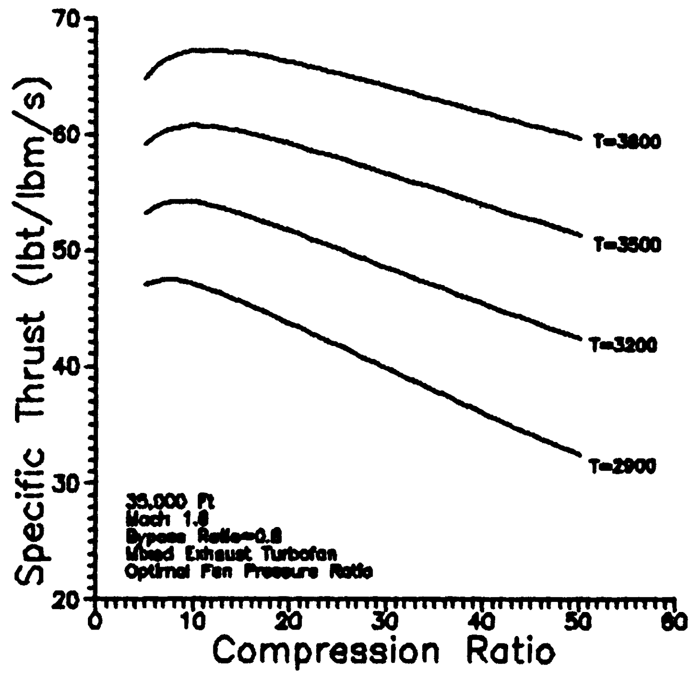

Figure 5-10

Variation in the Specific Thrust of a Low Bypass Ratio Turbofan With Compression Ratio and Turbine Inlet Temperature at Mach 1.6.

Increases in compression ratio may be still pursued for subsonic aircraft such as strategic bombers for which SFC is an important consideration. SFC can be recovered at higher turbine inlet temperatures by simultaneously increasing the pressure ratio of the engine. This effect results from the fact that the pressure ratio at which an engine achieves maximum thermal efficiency is typically higher than the pressure ratio for maximum specific thrust. Figure 5-11 plots thermal efficiency as a function of overall compression ratio for a mixed exhaust turbofan engine four different turbine inlet temperatures. The engine analyzed is the same as the one analyzed in Figure 5-9. By comparing this graph with Figure 5-9, one can see that the compressor ratio for maximum thermal efficiency is considerably higher than

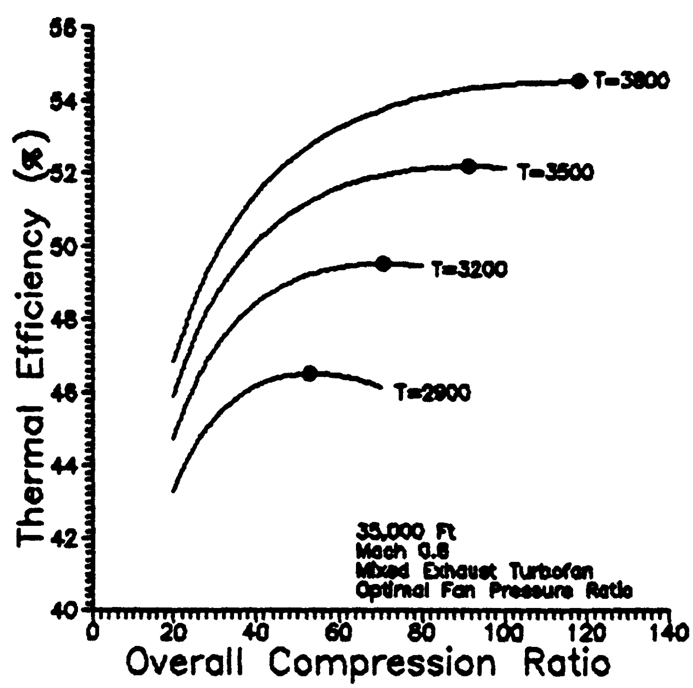

Figure 5-11. Thermal Efficiency as a Function of Compression Ratio for Four Different Turbine Inlet Temperatures.

that for maximum specific thrust. This result implies that the SFC of an engine can be improved by increasing the engine's compression ratio to the point of maximum thermal efficiency.

For a low-bypass ratio engine, an increase in compression ratio can decrease cruise SFC by 10-15%. Figures 5-12 and 5-13 demonstrate this effect for engines with design Mach numbers of 0.8 and 1.6, respectively. In both graphs SFC is plotted versus compression ratio for four different turbine inlet temperatures. At each turbine inlet temperature, increases in compression ratio from 10:1 to 40:1 decrease SFC by 10 to 15%. As a result an engine with a TIT of 3800°R and a compression ratio of 40 is more fuel efficient than an engine operating at 2900°R and a compression ratio of 15.

Thus, turbofan engines can be designed for increased specific thrust and for low SFC by simultaneously increasing turbine inlet temperature and compression ratio. This interrelationship leaves the designer with several choices in the design of an engine. These choices are displayed in Figure 5-14 which plots the tradeoff between specific thrust and SFC for combinations of TIT between 2900 and 3200°R and compression ratios between 30 and 80. If the base case is taken as 2900°R and a compression ratio of 30, characteristic of the F118 engine, it can be seen that increasing the TIT to 3800 degrees and increasing the compressor ratio to 80 increases the specific thrust of the engine from 59 to 78 lbt/lbm/s and actually lowers the SFC from over 0.95 to 0.93 lb/lbt/hr. Without the increase in pressure ratio, the engine would have an SFC of approximately 1.04 at 3800°. The loss in

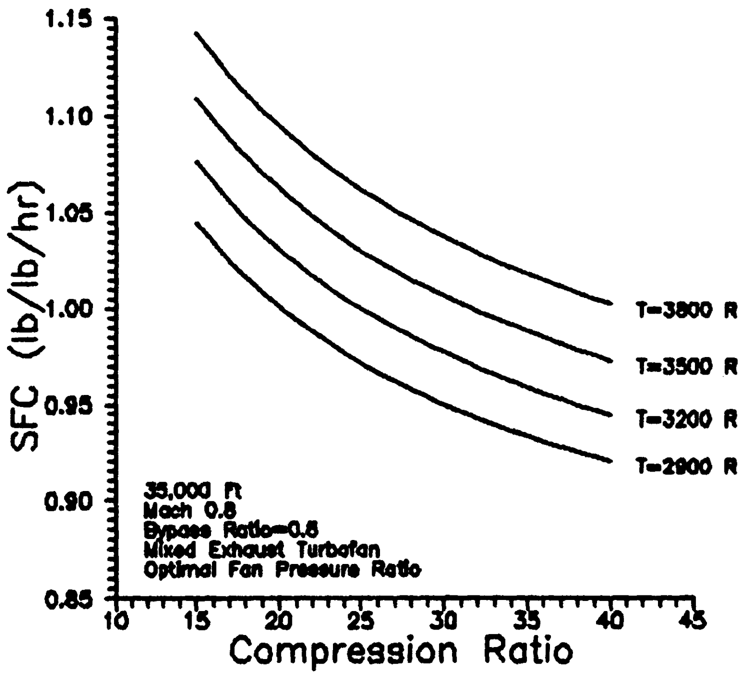

Figure 5-12

Variation in the Specific Fuel Consumption of a Low Bypass Ratio Turbofan with Compression Ratio and Turbine Inlet Temperature at Mach 0.80.

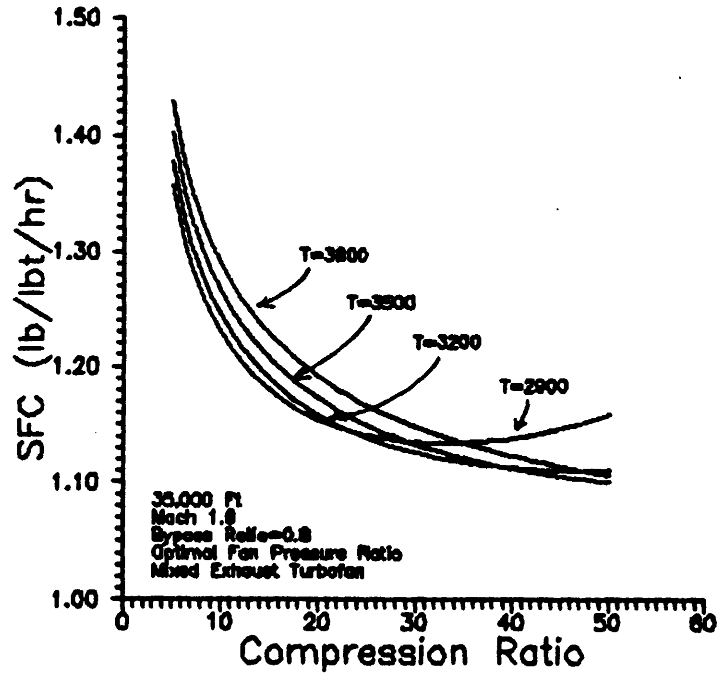

Figure 5-13

Variation in the Specific Fuel Consumption of a Low Bypass Ratio Turbofan with Compression Ratio and Turbine Inlet Temperature at Mach 1.6.

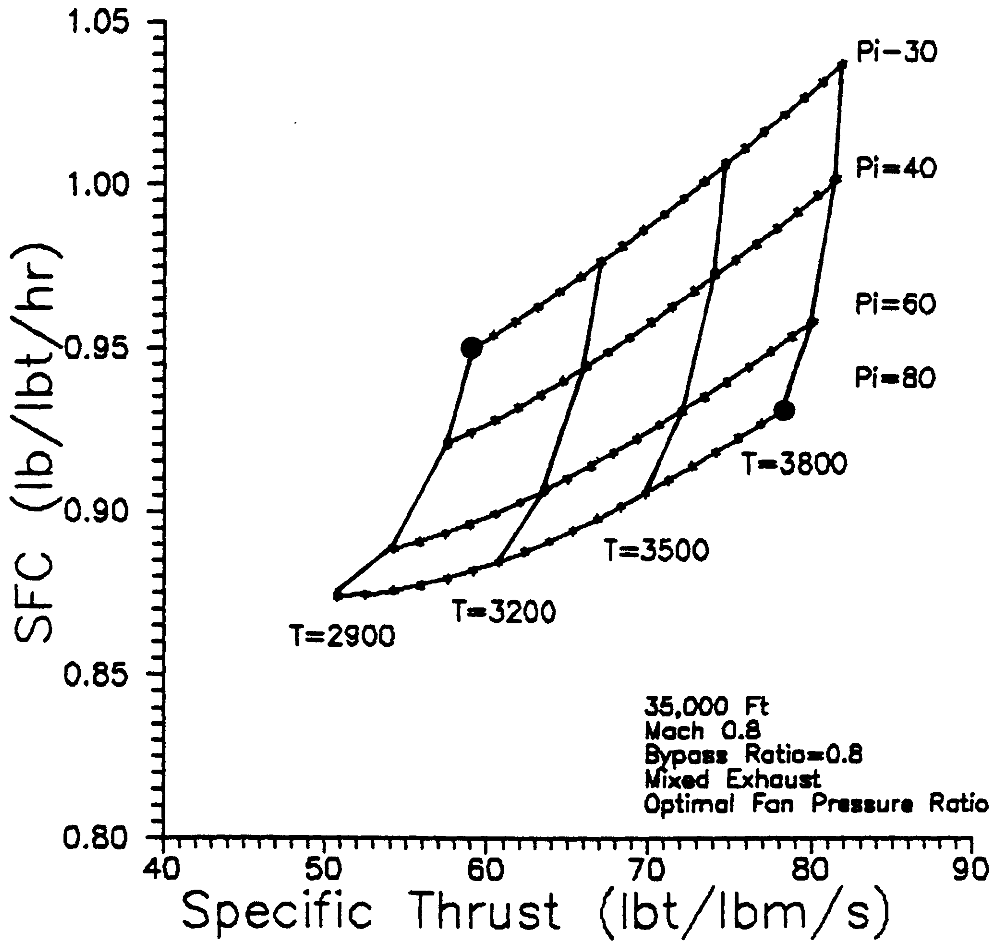

Figure 5-14. *Tradeoff Between Specific Thrust and SFC for Various Choices of Turbine Inlet Temperature (T) and Compression Ratio (Pi).*

specific thrust resulting from the increased compression ratio is minimal. Only 3 lbt/lbm/s is lost.

This analysis indicates that military interests in compression ratio will be dictated by the application for which new engines are designed. Fighter engines will probably not stimulate the design of higher pressure compressors as high pressure ratios are detrimental to performance at supersonic speeds. Subsonic aircraft, however, stand to benefit greatly from high pressure compressors as they allow SFC to be maintained or even improved as specific thrust increases.

Regardless of this difference, the military will most likely continue to pursue advances in compressor stage design. Both subsonic and supersonic engines can benefit from improved compressor stages as they will lead to lighter engines and thus improved thrust-to-weight ratios. The greater the pressure ratio that can be achieved with a single stage, the fewer stages will be needed to achieve a desired compression ratio and the lighter the engines will become.

The IHPTET program may generate technologies to be used in compressor design. In axial compressor design, the goal of IHPTET is to improve stage compression ratios by 25% with a 4% improvement in efficiency[4]. In addition, the use of metal matrix composites in stage construction will help reduce the weight of the compressor by up to 50%. Additional work is being directed toward fan blade design so that the number of fan stages used in a typical fighter engine can be reduced from three to two. In particular swept fan blades are being developed under IHPTET. These blades are swept forward at the root and backward at the tip in order to reduce tip speeds and shock losses (Interavia, 1989, p. 1114).

[4]Compressor stage efficiency will be described in the next section of the text.

4. Turbine and Compressor Efficiencies:

Further improvements in specific thrust can be achieved by improving the efficiency of the turbine and compressor. Turbine and compressor efficiencies are typically expressed in terms of the polytropic efficiency of the individual stages This efficiency characterizes the state-of-the-art in compressor design. The efficiency of a complete compressor or turbine can be computed by calculating the combined effect of the individual stage efficiencies. Polytropic efficiency defines the ratio of actual work required for a given incremental increase in pressure divided by the ideal amount of work required for a given incremental increase in pressure.

Improvements in compressor and turbine stage efficiencies can both increase specific thrust and decrease SFC. Inefficient stages result in larger temperature increases across a stage than would be expected from an adiabatic compression of a gas. By improving the efficiency of a stage, the temperature rise resulting from a given compression ratio will be decreased, allowing a greater temperature rise in the combustor. Figure 5-15 displays the effect of increasing compressor polytropic efficiency from 0.9 to 1.0 in an mixed exhaust turbofan engine with a turbine inlet temperature of 3200°R and a design point of Mach 0.8 at 35,000 feet. Fan pressure ratio is assumed to be optimized for specific thrust. As shown, the specific thrust of the engine increases from a maximum of 67.5 lbt/lbm/s to 75 lbt/lbm/s.

Optimal compression ratio also increases as polytropic efficiency increases. As shown in the graph, an increase in the polytropic efficiency from 0.9 to 1.0

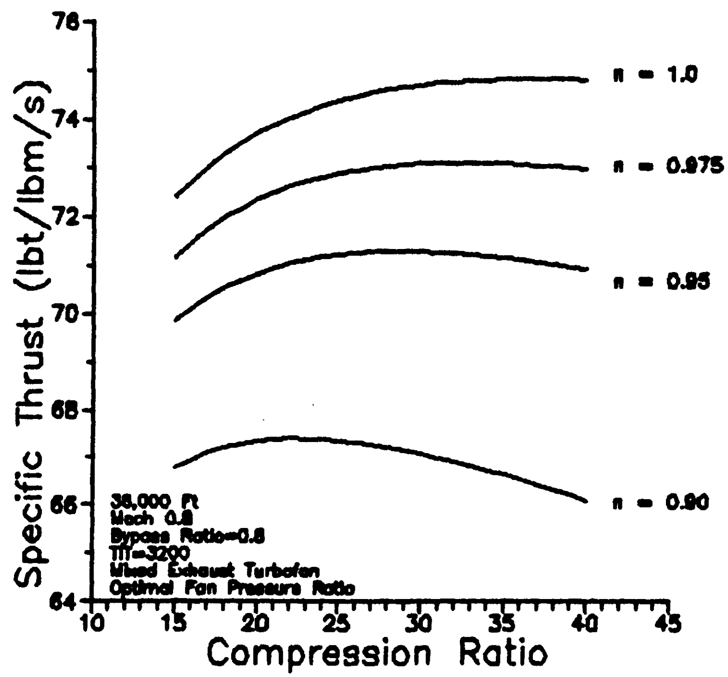

Figure 5-15

Effect of Polytropic Efficiency on Specific Thrust and Optimum Compression Ratio for a Low Bypass Ratio Turbofan.

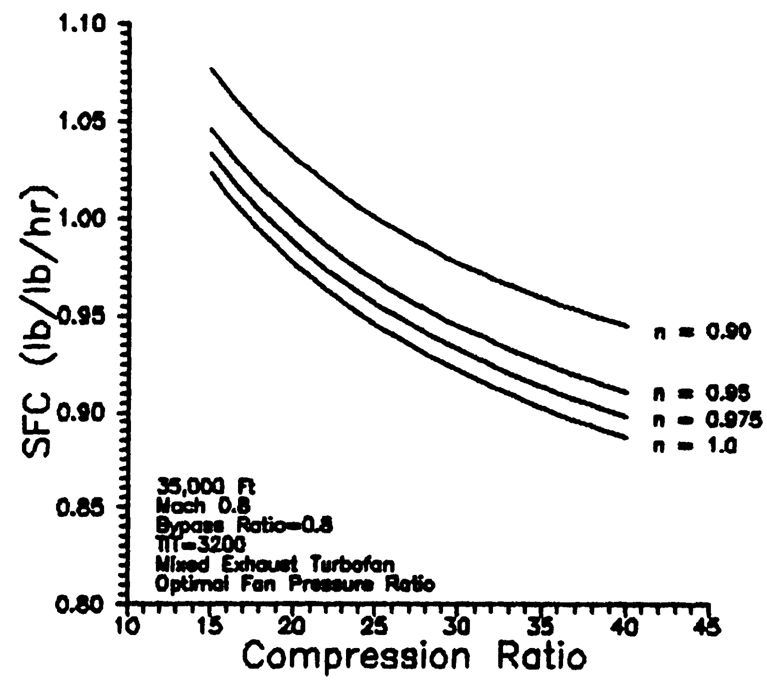

Figure 5-16

Effect of Polytropic Efficiency on the SFC of a Low Bypass Ratio Turbofan as a Function of Compression Ratio.

increases the optimum compression ratio from 22.5 to 36.0. This effect can be understood from an analysis of temperature considerations. A more efficient compressor will increase the temperature of the airstream less than an inefficient compressor. Thus, with more efficient compressor stages, the compression ratio required to bring the airstream to the desired temperature at the inlet to the combustor increases.

By increasing the compressor ratio, the SFC of the engine can also be improved despite the increase in core stream exhaust velocity. Figure 5-16 plots SFC versus compression ratio for four levels of polytropic efficiency. At each compression ratio, the SFC of the engine is improved. The relationship between specific thrust and SFC can be appreciated by plotting the two on the same graph. Figure 5-17 shows the tradeoff for all four levels of polytropic efficiency. Each point on each curve represents a different compressor ratio. As can be seen, even by operating at the point of maximum specific thrust on each curve, SFC can be steadily reduced.

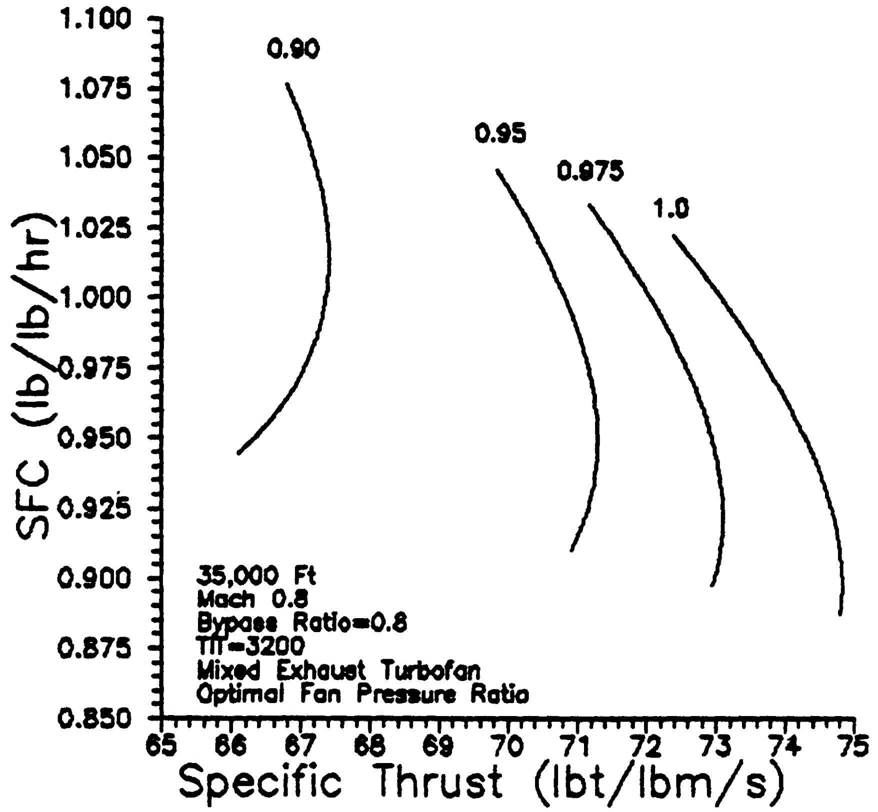

Figure 5-17. *Possible Tradeoffs Between Specific Thrust and SFC For Different Levels of Compressor and Turbine Polytropic Efficiency.*

5. Bypass Ratio:

Further improvements in specific thrust can be gained by decreasing the bypass ratio of military engines. The advantage of high bypass ratios is in their improved propulsive efficiency which, in turn, improves the SFC of the engine. However, this advantage is gained at the expense of specific thrust and with penalties in size and weight. As engine size, thrust-to-weight ratios, and specific thrust become more important in military engines, the design of these engines is likely to be characterized by decreased bypass ratios.

Supersonic engine design can benefit most from reduced bypass ratios. At all speeds, the net thrust of a gas turbine engine decreases steadily as its speed increases, regardless of bypass ratio. Thus, an engine that is powerful enough for subsonic flight may be severely underpowered for supersonic flight. By decreasing the bypass ratio of an engine, specific thrust can be recovered at high speed. The variation of specific thrust with design speed is shown in Figure 5-18 which plots specific thrust of a mixed exhaust turbofan with a pressure ratio of 30 for five different bypass ratios. Turbine inlet temperature is assumed to remain constant at 2900°R. As this graph demonstrates, specific thrust decreases by approximately 60% at all bypass ratios as Mach number increases from 0 to 2.0. Using a bypass ratio of 0.8 as a base case, one can see that the specific thrust generated at Mach 0.8 is just under 60 lbt/lbm/s. By decreasing the bypass ratio to 0.2, this same specific thrust level can be achieved at a speed of Mach 1.5 without otherwise modifying the design of the engine.

Decreases in bypass ratio are important in the design of engines for aircraft with supersonic cruise requirements in which the increase in specific thrust is of primary importance. However, for subsonic aircraft in which speed is not a primary design feature, decreased bypass ratios are detrimental because they increase the SFC of the engine and as a result reduce the maximum range of the aircraft. Figure 5-19 plots SFC versus design Mach number for five different values of bypass ratio. The engine has the same characteristics as that described above. At any given Mach number, a decrease in bypass ratio causes an increase in SFC. Some of this loss can be regained by increasing the compression ratio as described above.

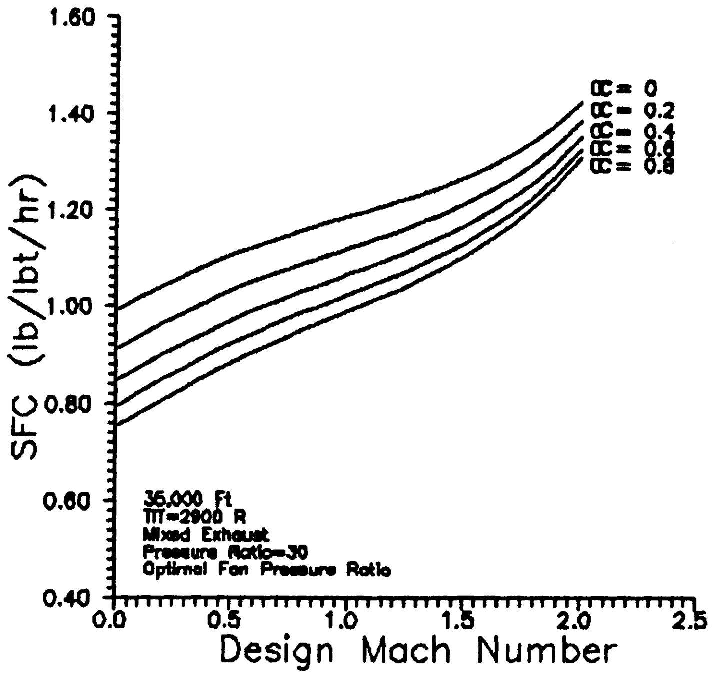

Figure 5-18

Influence of Bypass Ratio on the Specific Thrust of a Turbofan Engine at Mach Numbers Between 0 and 2.

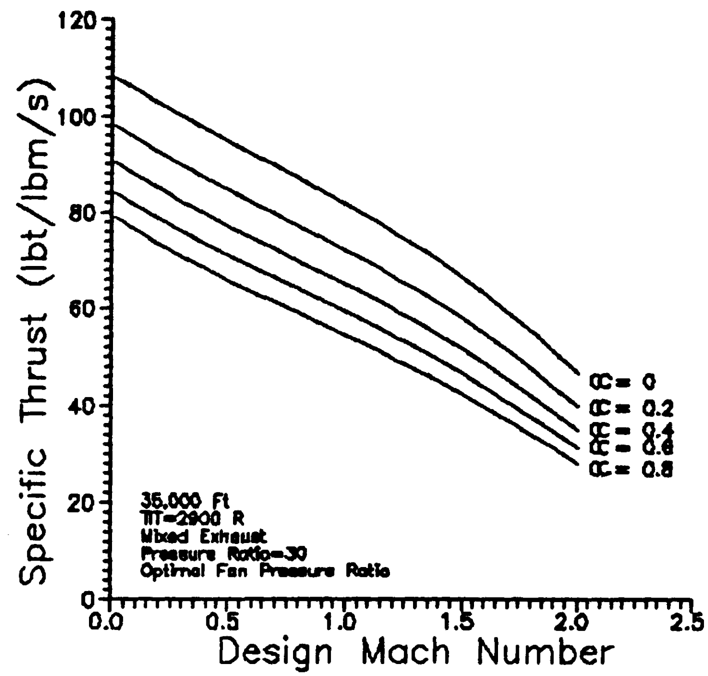

Figure 5-19

Influence of Bypass Ratio on the Specific Fuel Consumption of a Turbofan Engine at Mach Numbers Between 0 and 2.

Fighter engine design appears to be moving toward lower bypass ratios Whereas the Pratt & Whitney F100 engine designed to power the F-15 and F-16 has a bypass ratio of 0.69, the more recent F-404 designed by GE and used on the F-18, F-20, and F-117A has a bypass ratio of only 0.35. As a result, the F404 engine has a specific thrust of 78.6 lbt/lbm/s at sea-level compared to a value of 65.3 for the F100 engine (Gal-Or, 1990, p. 206). Its maximum diameter is only 35 inches compared to 46½ inches for the F100; and its weight is a full one-third less than the F100 (Aviation Week, 1991b, pp. 133-135).

ATF engine designs reflect the same trend. This engine is required to generate sufficient thrust to allow supersonic cruise capability without recourse to afterburners. This capability, referred to as "supercruise" will allow the ATF to use its supersonic capability for greater periods of time without sacrificing range (Dornheim, 1990, p. 44). Both competitors for the ATF engine have introduced low bypass turbofans in order to meet this requirement. The Pratt & Whitney engine, the YF119 is best described as a "leaky turbojet" engine although details regarding its bypass ratio have not been released. The GE entrant, the YF120, uses a variable bypass ratio to increase specific thrust at high Mach numbers. This engine operates as a turbofan at low speed, but by closing the bypass ducts at supersonic velocities, operates as a turbojet for high-speed flight.

B. Research Directions for Commercial Engines

The priorities driving research into commercial engines are the reverse of those for military engines. Development of engines for commercial application will focus on ways to improve specific fuel consumption without sacrificing specific thrust. Emphasis on SFC will enable new engines to operate more efficiently than the engines they replace and burn less fuel. The desire to maintain specific thrust derives from a desire to avoid the need to develop larger mass flow engines to produce the thrust needed by large jet airliners.

The SFC of an engine is directly related to its overall efficiency. Thus, SFC can be improved by increasing either the propulsive efficiency or the thermal efficiency of the engine. However, propulsive and thermal efficiencies are interrelated. Increases in thermal efficiency tend to increase the velocity at which the core stream is exhausted from the engine. The increased velocity of the core airstream, in turn, reduces the propulsive efficiency of the engine. However, as was demonstrated in Chapter II, the propulsive efficiency of a turbofan engines can be increased by raising the bypass ratio of the engine. Improvements in SFC can therefore be achieved by increasing the thermal efficiency of the engine core and then increasing the bypass ratio of the engine to regain propulsive efficiency.

1. Bypass Ratio:

The effect of increased bypass ratios upon engine performance was demonstrated briefly in Chapter II. As noted, the increased bypass ratio decreases the SFC of the turbofan, but simultaneously decreases its specific thrust. Figure

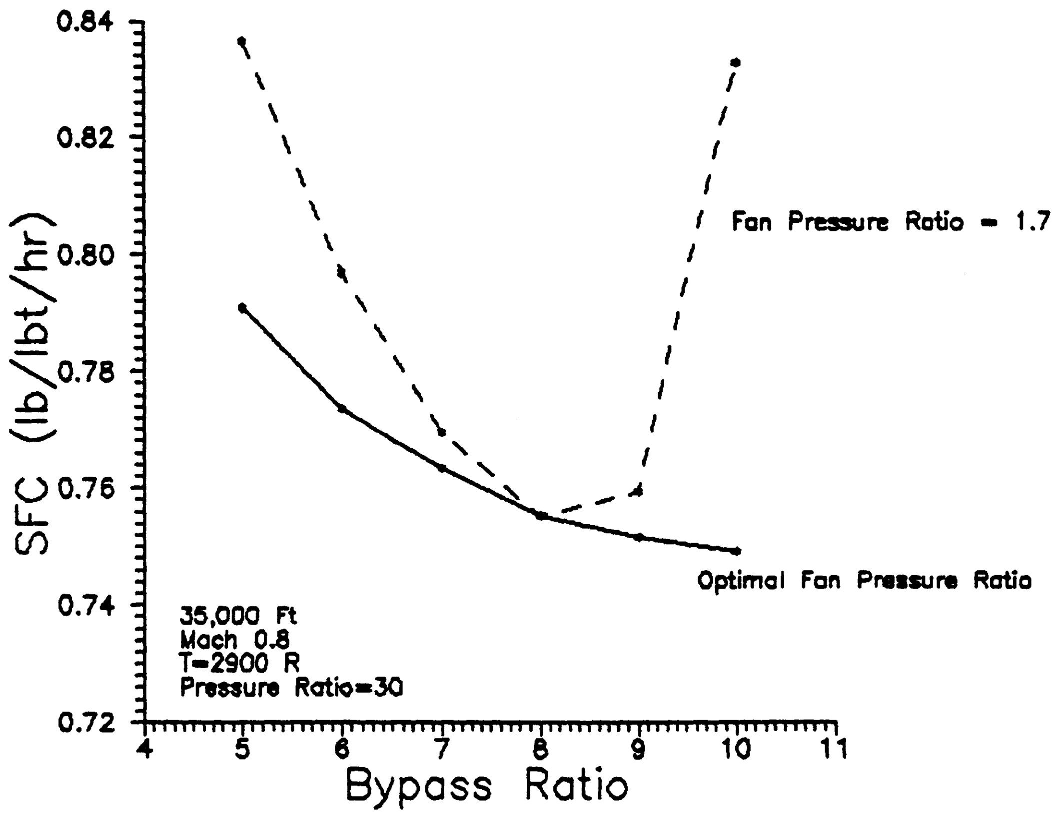

Figure 5-20. *Comparison of SFC as a Function of Bypass Ratio for Two Turbofan Engines: One With a Fixed Fan Pressure Ratio of 1.7; the Other With an Optimal Fan Pressure Ratio Matched to the Bypass Ratio.*

5-20 plots the SFC of a turbofan engine versus bypass ratio. The engine was assumed to have a maximum turbine inlet temperature of 2800°R and an overall pressure ratio of 30, consistent with current commercial turbofans such as the PW4000 engine. Other engine parameters are shown in Table 5-3 and are also representative of current high bypass ratio turbofans. Two curves are plotted in this graph. The solid curve plots the SFC of an engine in which the fan pressure ratio is matched to the bypass ratio. The dashed curve plots the SFC for a

Table 5-3

Parameters for Base Case Commercial Engine

Parameter	Value
Bypass Ratio	5.0
Maximum Turbine Inlet Temp. (°R)	2800
Overall Compression Ratio	30
Polytropic Efficiency: Turbine	0.90
Polytropic Efficiency: Compressor	0.90
Cooling Air Flow (Each Spool)	5%

turbofan engine with a fixed fan pressure ratio of 1.7 which is the current limit for a single stage fan. Because of the extra weight additional fan stages would contribute to the overall engine weight, most current high bypass turbofans use only a single fan stage. For bypass ratios less than eight, the engine is optimized with a fan pressure ratio over 1.7. Since such levels cannot be achieved with current technology, the SFC of this engine at low bypass ratios is more accurately portrayed by the dashed line. Above bypass ratios of eight, the engine is optimized with a fan pressure ratio less than 1.7; thus, the solid line is more representative of optimal performance.

The actual tradeoff between SFC and bypass ratio is shown in Figure 5-21. This graph combines the two curves shown in Figure 20. For bypass ratios less than eight, the fan pressure ratio is assumed to equal 1.7. For higher bypass ratios, the optimal fan pressure ratio is used. As this graph demonstrates, the SFC of this engine can be significantly reduced (by 15% in this case) by increasing the bypass ratio. The greatest portion of this improvement in SFC can be achieved by increasing the bypass ratio to eight, though further reductions are possible with larger bypass ratios.

Increasing bypass ratio, however, simultaneously reduces the specific thrust of the engine. Figure 5-22 shows the change in specific thrust for the engine studied above caused by the change in bypass ratio. Specific thrust decreases almost linearly with bypass ratio so that from a bypass ratio of five to a bypass ratio of 10, specific thrust decreases from 18.8 to 11.5. This reduction in specific thrust would require the mass flow through the engine to be increased by 40% in order to maintain the original thrust level of the engine. In effect, this would require that the size of the engine be increased, increasing its weight and drag.

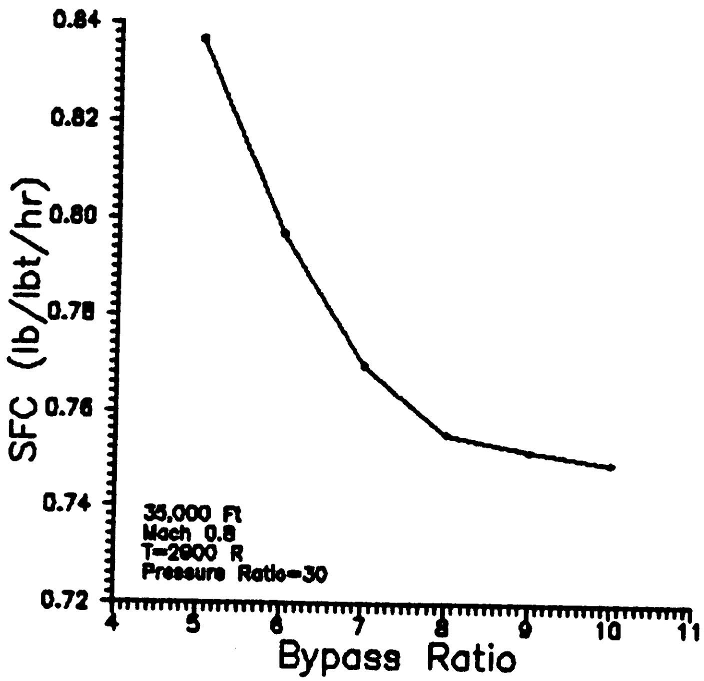

Figure 5-21

The Effect of Bypass Ratio on the Specific Fuel Consumption of a Turbofan Engine at Mach 0.80.

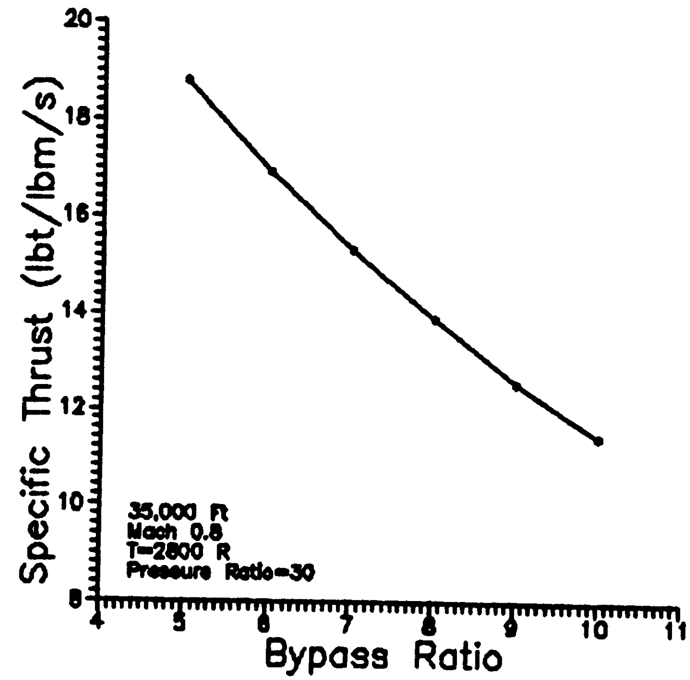

Figure 5-22

The Effect of Bypass Ratio on the Specific Thrust of a Turbofan Engine at Mach 0.80.

2. Turbine Inlet Temperature:

Some of the loss in specific thrust can be regained by increasing the turbine inlet temperature of the engine in order to improve its thermal efficiency. The result of this change is shown in Figure 5-23 which compares the specific thrust of an engine operating with a turbine inlet temperature of 3200 degrees with that of the 2800 degree engine explored above. This curve was calculated assuming a constant pressure ratio of 30. In addition, as the optimal fan pressure ratio for an engine at 3200 degrees is above 1.7, a constant fan pressure ratio of 1.7 was used in this analysis. As shown, the increase in turbine inlet temperature improves the specific thrust of the engine by about 15% at all bypass ratios. By examining the graph, one can see that the bypass ratio of the 3200 degree engine can be increased to about 7 with no appreciable loss in specific thrust as compared to the 2800 degree engine with a bypass ratio of 5.

The effect of the temperature increase on SFC is shown in Figure 5-24. This graph displays a surprising result. Whereas the hotter engine has a higher SFC for bypass ratios less than 9 as might be expected, it has a lower SFC than the cooler engine at bypass ratios above 9. As this graph demonstrates, higher bypass ratio engines are optimized at higher turbine inlet temperatures (assuming other design factors are held constant). This effect results from the interplay between thermal and propulsive efficiencies. At low bypass ratios, the propulsive efficiency of the cooler engine is substantially higher than that of the hotter engine because its airstream is exhausted at a lower velocity. Thus, despite the higher thermal efficiency of the hotter engine, the overall efficiency of the cooler engine

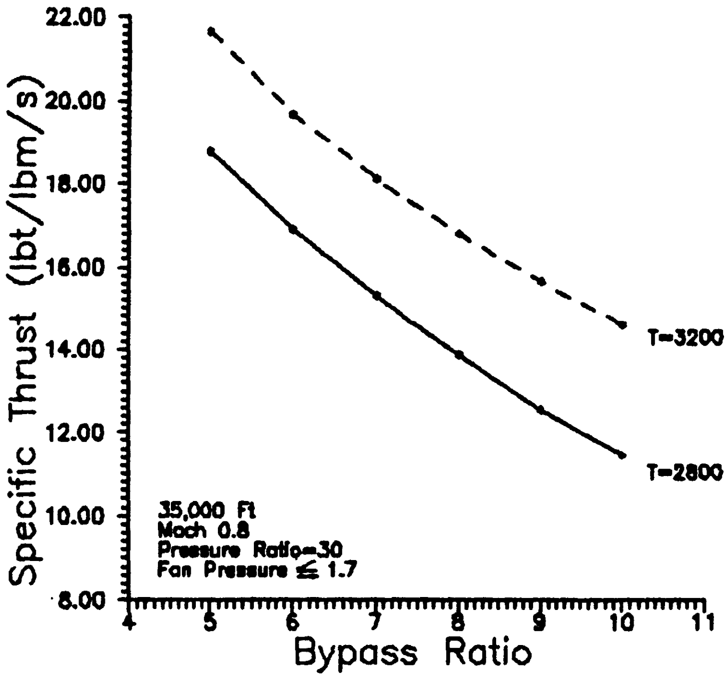

Figure 5-23

Comparison of Specific Thrust as a Function of Bypass Ratio for a Turbofan Engine with a TIT of 3200°R and a Turbofan Engine with a TIT of 2800°R.

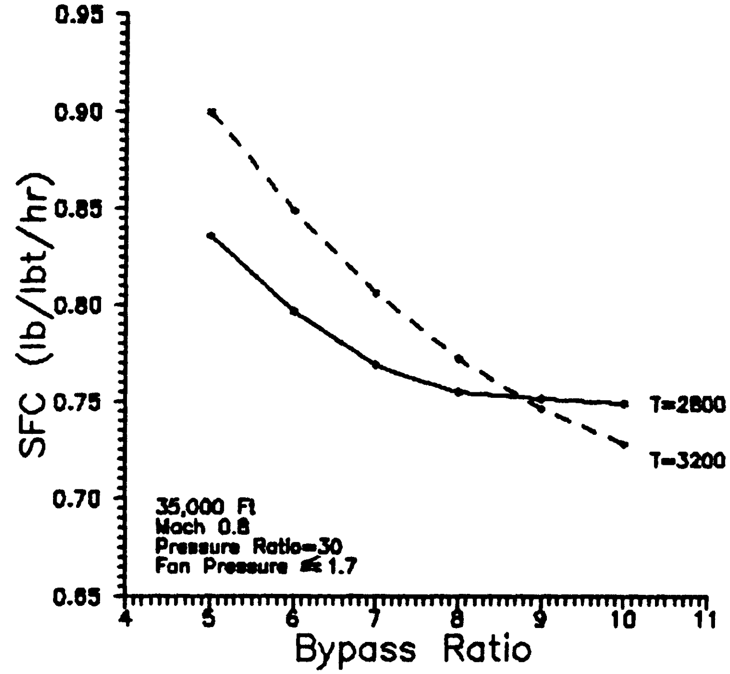

Figure 5-24

Comparison of SFC as a Function of Bypass Ratio for a Turbofan Engine with a TIT of 3200°R and a Turbofan Engine with a TIT of 2800°R.

is higher. As bypass ratio is increased, the propulsive efficiency of both the high and low temperature engine increases. For large bypass ratios, the propulsive efficiency of both engines approaches unity. However, because of its higher turbine inlet temperature, the hotter engine has a higher thermal efficiency. Thus, the overall efficiency of the hotter engine and its SFC will be superior to that of the cooler engine.

3. Compressor Pressure Ratio:

Additional improvements in specific fuel consumption can be achieved by increasing the overall pressure ratio of the engine. As was shown earlier for military engines, the compression ratio at which an engine achieves maximum thermal efficiency is much larger than the compression ratio at which it achieves maximum specific thrust. Thus, SFC can be reduced by increasing the compression ratio of high bypass turbofan engines. Figure 5-25 shows the effect on SFC of increasing the pressure ratio of the 3200°R engine from 30 to 50. SFC is plotted versus bypass ratio and compared to the base case with a turbine inlet temperature equal to 2800°R and a pressure ratio of 30. The increased pressure ratio decreases the SFC of the hotter engine at all bypass ratios and lowers the bypass ratio at which the higher temperature engine becomes more efficient that the cooler engine. As shown in this figure, the engine with a 3200 degree turbine inlet temperature and the pressure ratio of 50 becomes more efficient than the base engine at bypass ratios above six. Moreover, as shown in Figure 5-26, the specific thrust of the hotter engine with a bypass ratio of six is higher than that of the cooler engine at its original bypass ratio of 5. Thus, the improved SFC can be

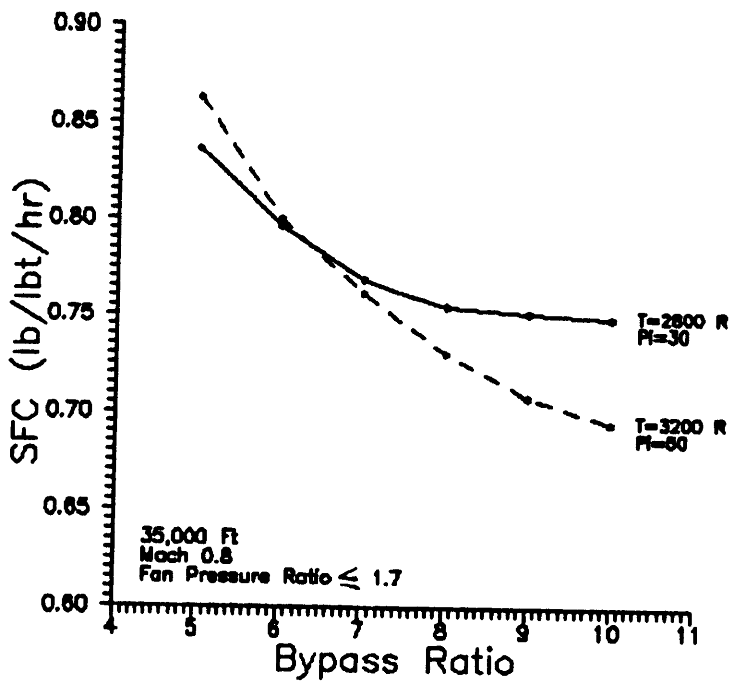

Figure 5-25

Comparison of the Specific Thrust of a Turbofan Engine with a TIT of 2800°R and a Compression Ratio (PI) of 30 to the Specific Thrust of a Turbofan with a TIT of 3200°R and a Compression Ratio of 50.

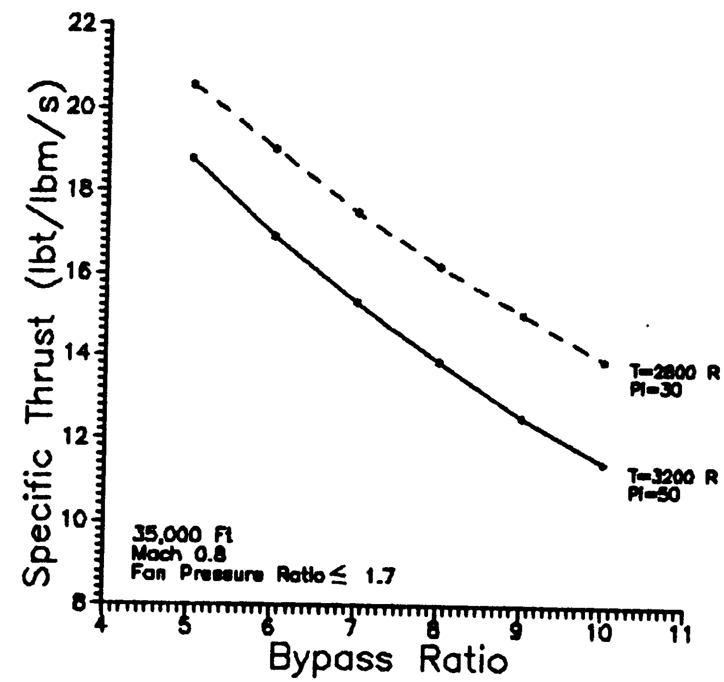

Figure 5-26

Comparison of the SFC of a Turbofan Engine with a TIT of 2800°R and a Compression Ratio (PI) of 30 to the SFC of a Turbofan with a TIT of 3200°R and a Compression Ratio of 50.

gained without any loss in thrust. Additional increases in bypass ratio to further reduce SFC would, however, require an enlargement of the fan to generate sufficient mass flow through the engine and maintain a constant thrust rating.

Several manufacturers are now exploring the benefits of ultra-high bypass ratio engines. These engines have bypass ratios between 9 and 25. Pratt & Whitney and General Motors' Allison Gas Turbine Division have jointly developed a demonstration version of an ultra-high bypass engine designated the Advanced Ducted Propeller (ADP) engine. Pratt has proposed a production version of this demonstrator as a possible contender for the new Boeing 777 should the thrust requirement for that aircraft continue to grow. The ADP is a turbofan engine that can have a bypass ratio between ten and twenty-five to one. This extremely high bypass ratio gives the ADP extremely low SFC, though a specific figure has not yet been released. The current demonstrator engine is powered by a PW2000 core section. Because the PW2000 has a sea-level static mass airflow of only 200 pounds per second, the current ADP is limited in thrust to smaller widebody twin jet aircraft or larger four-engine jets such as the 747. With a PW4000 core, the engine could become powerful enough to power a heavier version of the 777.

General Electric has also developed an ultra-high bypass engine that it is proposing for the 777. This engine, the GE90, has a bypass ratio of 9:1 and an overall compression ratio of 40. The compressor itself has a pressure ratio of 23:1, compared to the current standard of 15:1. As a result, the bare engine has a maximum thrust rating of 86,800 pounds and a SFC that is 8-10% lower than its competitors (Interavia, 1991, p. 14). According to *Aviation Week & Space Technology* (1991b, p. 133), this engine has a sea-level, static SFC of only 0.278 lb/lbt/hr. The GE90 is an entirely new engine, scaled from the engine GE designed and demonstrated as a participant in NASA's Energy Efficient Engine (E^3) project (Taylor, 1990, p. 733). During this program, GE developed an engine with a bypass ratio of seven and an SFC at takeoff of 0.299 lb/lb/hr (Davis and Stearns, 1985).

4. Advanced Nacelle Design:

The large increase in bypass ratio associated with ultra-high bypass engines requires an increase in the total mass flow through the engine in order to generate acceptable levels of total net thrust. As a result, these engines use large nacelles to duct the airstream through the core and bypass regions. The nacelles themselves generate additional drag, and negate some of the SFC benefit of the higher bypass ratio. The GE90, for example, has an uninstalled SFC 8-10% better than the engines it is intended to replace. When installed on an aircraft in its larger nacelle, however, the engine has an effective SFC only 3 to 5 percent better than the competition.

Nacelle drag becomes significant as bypass ratio is increased. For large increases in bypass ratio, the additional nacelle drag may completely negate reductions in SFC gained by the improved propulsive efficiency. Figure 5-27 shows the effect of nacelle drag on SFC for a high bypass ratio turbofan engine with a turbine inlet temperature of 3460°R and an overall pressure ratio of 100 as the bypass ratio is increased. This figure is reproduced from Glassman (1989, p. 9) and assumes constant core technology (in terms of component efficiencies, etc.) and an optimal fan pressure ratio as shown on the *x*-axis. Several curves are plotted on this graph. The top curve shows the effect of increased bypass ratio on engine SFC assuming no nacelle losses. As expected, SFC increases monotonically with bypass ratio. The effect of nacelle losses is included in the lower curve. As this curve shows, with current nacelle designs nacelle losses negate gains in propulsive efficiency for bypass ratios above 11. In fact, for bypass ratios above 16, the nacelle losses may outweigh the benefits of increased bypass ratio and actually increase the SFC of the engine.

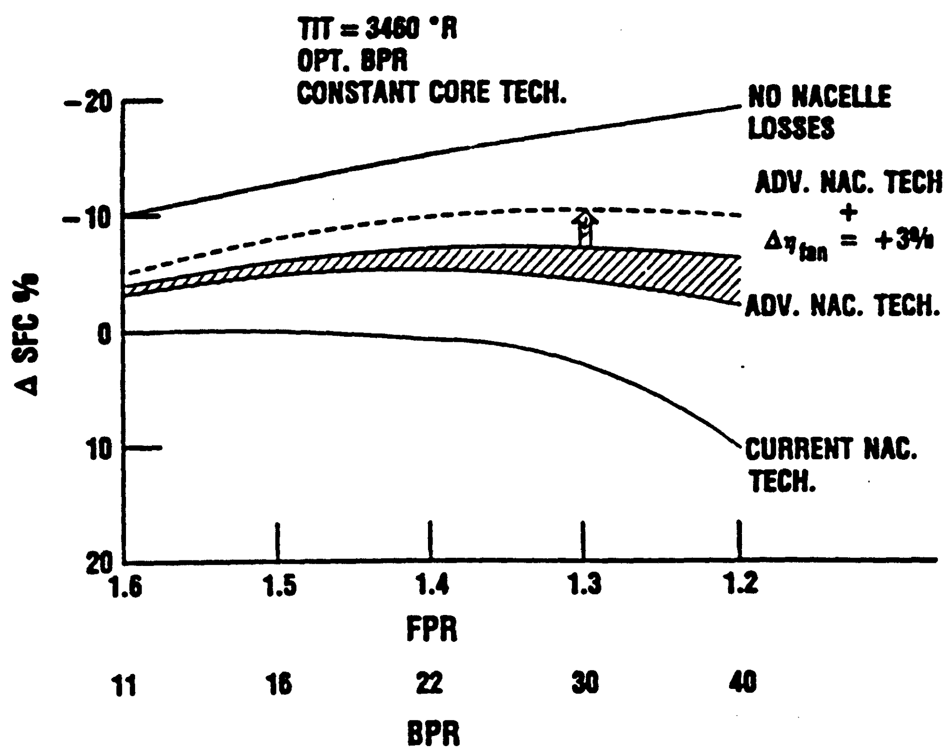

Figure 5-27. Effect of Nacelle Technology Upon Engine Installed SFC as a Function of Bypass Ratio and Fan Pressure Ratio [From Glassman, 1989, p 9].

Research on advanced nacelles is directed at reducing the effects of nacelle drag. The middle curves in Figure 2-27 demonstrate the effect that advanced nacelles and advanced nacelles plus improved fan efficiency may have upon engine SFC. The shaded band represents differing estimates of the success of these programs. Such programs appear necessary in order to allow further improvement in SFC with bypass ratio.

5. Unducted Fan Engines (Propfans):

In order to increase bypass ratio without the penalty imposed by nacelle drag, both Pratt & Whitney and GE have begun developing unducted fan engines or propfans. In these engines, the fan blades are positioned near the rear of the engine and exposed to the incoming airflow without a nacelle to diffuse the airstream and lower its velocity. Without the nacelle, the drag penalty imposed upon these engines by their large bypass ratios is negligible. However, since the incoming airflow is not diffused by the nacelle, blade design becomes more difficult.

Without a nacelle to diffuse the incoming airstream, the fan blades are exposed directly to the incoming airflow. The velocity of the fan blade tips with respect to the airflow is therefore the vector sum of the flight velocity of the aircraft and the rotational velocity of the blades. As a result, the blades reach sonic velocities at relatively low rates of revolution. In order to overcome the problems associated with shock wave formation, the fan blades must be swept back at the tips and set at an extreme angle to the airflow. Both the GE and Pratt engines use scimitar-shaped fan blades. However, even with sophisticated blade shaping, the size of the blades and hence the total mass flow through the engine is limited. These limitations restrict the thrust levels achievable with propfan technology. Further research in this area will undoubtedly be necessary to further improve the efficiency of the propfan.

The advantage of propfans is that they promise large reductions in SFC because of their large effective bypass ratios. The GE engine, the Unducted Fan (UDF) engine has a bypass ratio of 36 and a sea-level thrust rating of 25,000 pounds. The SFC of this engine at takeoff is only 0.24 (Gray and Conliffe, 1990, p. 34). The Pratt-Allison engine has a bypass ratio of 60 and is rated at 20,000 pounds of thrust. Its SFC rating has not yet been published (Gray and Conliffe, 1990, p. 35).

Further reductions in engine weight will have to be achieved, though, before propfan engines become practical for commercial application. Because of their unducted fan blades, acoustic properties, and aerodynamic characteristics, propfan engines must be mounted on the rear fuselage of aircraft rather than below the wings (Interavia, 1989, p. 1116). The additional weight at the tail alters the stability of the aircraft. In order to compensate for this additional weight, the length of the tail arm must be reduced and the size of the tail control surfaces must be increased. These changes reduce the efficiency of the aircraft as a whole.

Until lighter weight engines can be developed, therefore, the unducted fan engine may not prove to be a viable commercial engine. GE, in fact, after developing a production model of its UDF engine has temporarily shelved the technology until a market for it should appear (Taylor, 1990, p. 735). Military research into new materials and more efficient compressor stages may prove applicable to propfan engines as it would help lower the weight of these engines.

C. Future Commercialization and Technology Transfer

This analysis indicates that the overall character of engine technology transfer between military and commercial applications may in the future differ from the technology transfer characteristic of the early U.S. jet aircraft engine industry. Whereas early technology transfer was based upon a nearly direct transfer of complete engines and their cores to the commercial sector, future technology transfer will most likely involve the transfer of basic technologies and research results from military to commercial programs. Designs for military engines will differ radically from those for commercial engines, yet much of the military's research in materials and compressor design for advanced engine cores will be equally applicable to commercial engines. Interestingly, the only transfer of complete hardware between the two sectors may be the transfer of commercial high bypass ratio turbofans to military transport aircraft.

1. Direct Commercialization of Military Engines:

As noted, the engines developed for military and commercial applications will continue to diverge. Most military engine development is currently and will likely continue to be directed toward fighter engines and their upgrades. Since the 1950s, only two engines have been developed for bomber aircraft, the JT3 for the

B-52 and the F101 for the B-1. The only upgrade to these engines was the addition of a front fan section to the JT3, converting it into a turbofan. Several fighter-class engines have been developed over the past two decades, including the F100, F110, F404, and the ATF engines. Upgraded versions of all but the ATF engine have been produced. These engines are unsuitable for the commercial aircraft industry. Not only do they generate insufficient thrust to power large airliners, but their SFCs are approximately double those for commercial high-bypass turbofans. Most likely, future military engines will have even lower bypass ratios than present engines. Thus, the prospects for direct commercialization of military engines appear slim.

On the other hand, the military may expect to benefit from the "militarization" of commercial engines for military transport aircraft. Military requirements for such engines are similar to the requirements for commercial engines: high thrust and low SFC. Because military transports are designed for neither supersonic speed nor stealth, the size, weight, and installation requirements of high bypass turbofans do not impede aircraft performance. Moreover, with strong commercial demand for improved high bypass ratio turbofans, the military has little incentive to dedicate additional funding to this technology. Having demonstrated and validated the original high-bypass engine technology, the military may now leave further development to the commercial sector.

2. Commercialization of Military Engine Cores:

Prospects for the commercialization of military engine cores will be determined by three primary factors: specific thrust, design mass flow, and overall pressure ratio. In order for commercial engines to use military cores, these cores must be designed for high specific thrust, low core mass flow, and high overall pressure ratio. As highlighted in the previous section of this chapter, improvements in engine SFC will be pursued in the commercial sector by the development of higher bypass ratio engines. At the same time, the increase in bypass ratio must be achieved with as small an increase in overall engine size as possible. Clearly, the bypass ratio of an engine can be raised by increasing the diameter of the engine and passing more air through the bypass stream, but the extent to which such increases can be achieved is limited by the maximum diameter of the engine. In order to be installed on an aircraft, the engine must fit under the wing with adequate ground clearance. Thus, the true objective of high bypass ratio turbofan development will be to increase the bypass ratio of the engine without increasing its total mass flow. This result can be achieved by decreasing the size of the core flow. For example, consider an engine with a total mass air flow of 1200 lbm/s, 200 lbm/s of which passes through the engine core and 1000 lbm/s of which bypasses the core. This engine has a bypass ratio of 5. However, if the total mass flow is held constant so that the engine size is also held constant, and the core air flow is reduced to 100 lbm/s by constructing a smaller engine core, the bypass ratio of the engine will increase to 1100/100 or 11 to 1.

While such a change in design would greatly reduce SFC, the specific thrust of the engine would be significantly reduced. By increasing the specific thrust of the engine core, by such means as increasing the maximum turbine inlet temperature, the specific thrust of the overall engine could theoretically be returned to its original value. But, as shown previously, the compression ratio of the engine would also need to be increased to retain the gain in SFC. Thus, commercial engine requirements will be characterized by an increase in core specific thrust through higher turbine inlet temperatures and improved core efficiency, a decrease in the size of the core, and an increase in compression ratio.

The degree to which military engine cores will meet such characteristics will depend on the application for which they are designed. As noted, the design of fighter and bomber engines may begin to diverge as fighter engines are optimized for supersonic capability. In fact, fighter engine cores may not be suitable for commercial application. While they will be designed for higher turbine inlet temperatures as required by commercial engines, and will generate high levels of core specific thrust as further required by commercial engines, they will most likely not be designed for reduced mass flows. Instead, the mass flow will most likely be held relatively constant so that the total thrust of the engines will increase with the increase in specific thrust. As noted, the military has a requirement for high thrust engines to power aircraft with supercruise capability. Thus, the size of the engine may not be decreased as specific thrust is increased because increases in total thrust are desired. Should supersonic cruise capability remain a requirement for military engines, the new cores developed for these engines may not be applicable to commercial engines.

Engine cores developed for bombers hold more promise for commercial application. As these engines will most likely be designed for subsonic flight, they will be designed not for increased total thrust, but for increased specific thrust so that the total mass flow through the engine--and hence engine size--can be reduced. In this manner, they can be more easily be integrated onto stealthy platforms. Low SFC will also remain a requirement for future bomber engines. Thus, they may be designed with the high compression ratios desired in commercial turbofans. However, it is not clear that the military will develop many new bomber engines. The future of the strategic bomber force is at present uncertain. With the decline in the Soviet threat and the rising cost of new bombers, the structure of the strategic bomber force is likely to change over the next several decades. Moreover, even if a new bomber should be designed, the military may opt to adapt a fighter engine for its next bomber as was done on the B-2 in order to reduce development costs.

3. Transfer of Basic Technologies:

Despite the growing divergence between military engines and their commercial counterparts, military research on advanced core design holds much potential benefit for the commercial industry. In order to increase the specific thrust and thrust-to-weight ratios of military engines, advances in core design will be required. In particular, emphasis will need to be placed on the development of new turbine materials to increase the maximum turbine inlet temperature of military engines, to reduce the cooling air requirements, and to reduce engine weight. Improvements in component efficiencies will also aid in increasing specific thrust. Further research on compressor and fan stage design will help lighten military engines.

These core technologies are all applicable to commercial engine design. As demonstrated, increases in turbofan bypass ratios necessitate higher turbine inlet temperatures in order to simultaneously improve specific thrust and minimize SFC. Losses in specific thrust associated with increased bypass ratios must be offset by increases in turbine inlet temperature. Furthermore, higher bypass engines are optimized for fuel efficiency at higher temperatures than are lower bypass ratio engines. Maximal thermal efficiency is also achieved at higher pressure ratios than can be achieved with present technology. Thus, while military interests in high compression ratios may be limited to bomber engines, military research into improved compressor stage design for both fighter and bomber aircraft will apply to commercial compressor design. Greater pressure ratios per stage will allow increases in overall pressure ratio without increasing the weight of the compressor.

Not all basic technologies required to improve commercial engines will be addressed by military research programs. Advanced nacelle design for ducted fan engines and fan blade design for large propfan engines are unlikely to be developed for military applications[5]. To date, much of the research in these areas has been funded by the commercial engine manufacturers and by NASA. Through

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[5]The military had expressed some interest in propfans for cruise missile applications, but such interest appears to be waning. In addition, because of their smaller blade size, propfans developed for cruise missiles would probably not present the same design challenges to developers.

its Aircraft Energy Efficiency (ACEE) program initiated in the late 1970s, NASA has supported the Energy Efficient Engine program and the Advanced Turboprop program. The first of these was intended as a means of promoting the development of more fuel efficient turbofans through increased bypass ratios and improved core designs. The precursor to GE's GE90 ultra-high bypass engine was developed under this program (Davis and Stearns, 1985). The Advanced Turboprop Program was begun as a long-term initiative to develop propfan technologies for commercial use. Both the GE UDF and the Pratt-Allison propfan trace their heritage to research conducted as part of this program. As military interest in such technologies was limited, and fuel prices were expected to rise significantly, Congress authorized NASA to lead these development efforts.

As this discussion demonstrates, the nature of technology transfer between the military and commercial jet aircraft engine sectors will differ significantly from the commercialization that characterized the early engine industry. This change, coupled with changes in the nature of the aviation industry as a whole, have strong implications for the U.S. jet aircraft engine industry. These implications will be explored in the next chapter.

CHAPTER VI

POLICY IMPLICATIONS

This thesis was begun with three major goals in mind. The first was to examine the relationship, past and present, between commercial and military jet aircraft engine development in the U.S. The hope was that the role of the military in establishing and maintaining the early commercial jet engine industry could be uncovered and the importance of military R&D to this industry revealed. The second goal of this thesis was to examine the engine characteristics and technologies likely to be sought by commercial and military customers in the future in order to anticipate changes in the relationship between the military and commercial sectors of the engine industry. In particular, areas of divergence between future military and commercial engine research and development were to be identified. The third goal of this thesis was to provide guidance to government and business policy-makers for assuring the continued success and competitiveness of the U.S. jet aircraft engine industry.

Chapters III through V addressed the first two primary goals of this research. This chapter attempts to conclude the analysis. Particular attention is paid to understanding the implications of the earlier analysis on the development of policies to help promote the future success of the U.S. jet aircraft engine industry. Though the following discussion will identify issues to be addressed in future policy formulation, in many cases, further research will have to be conducted in order to fully evaluate the suggestions provided herein and to devise plans of implementation should they appear tractable. Nevertheless, this chapter should provide some direction for those later efforts.

A. Lessons Learned

At this point it seems appropriate to review the analysis presented so far in this thesis in order to highlight the conclusions that have significant policy implications. The conclusions presented below are based upon the analyses in Chapters III through V.

1. The Significance of Military R&D:

The U.S. military played a significant role in the establishment of the jet aircraft industry in the United States and in the eventual expansion of that industry into commercial operations. Early jet engine development was funded solely by the military and directed toward military goals, namely increasing the speed and altitude capabilities of its fighter and bomber aircraft. Early commercial interest in jet engines was hindered by considerations of cost-effectiveness. Until the development of the turbofan, jet engines were not powerful enough nor fuel efficient enough to be commercially competitive with propeller-driven engines. Early research and development in jet engine technology was conducted by companies brought into the jet engine industry by the government, specifically General Electric. Only after the technology was developed and somewhat established did another entrant succeed in breaking into the industry. This structure assured that engine development proceeded in accordance with military requirements.

Nevertheless, military R&D generated the technological base from which commercial products were derived. The requirements of the commercial airline industry were met with the same technology developed by the military. Thus, military research was essential in developing and validating technologies for commercial application. The development and validation of the axial-flow turbojet which allowed the first commercial application of jet technology and the later development of the high bypass turbofan which has since become the backbone of the commercial engine industry were both funded through military programs. In these cases, it is unlikely that the technology could have been developed without military funding because of the large developmental risks involved. Engine manufacturers could not provide the performance guarantees required by commercial airlines; nor could they guarantee the financial success of such projects to potential commercial investors. The military is less risk-averse than commercial industry in funding technical R&D, and its funding allowed engine manufacturers to overcome large technological obstacles associated with development of the jet aircraft engine.

Military interest in jet technology has also benefitted commercial industry by providing financial and capital resources that corporations could then devote to other areas of commercial engine research. Government procurement of engines generated funds for the establishment of the production facilities needed for both commercial and military production of engines. In an industry in which development of a new commercial engine can cost over a billion dollars and profits can be made only after long lead times, such capital is especially significant.

2. The Changing Relationship:

The relationship between military and commercial engine development is changing at present and will continue to change over the next several decades. Military interests in engine development appear strongly influenced by the desire for sustained supersonic flight. However, subsonic flight will continue to dominate commercial aviation for some time. As a result, military and commercial requirements for aircraft engines are diverging and the same engine designs will no longer serve both sectors of the industry. Whereas military requirements emphasize increases in specific thrust and thrust-to-weight ratios, commercial requirements are dominated by the desire for decreased operating costs and lower specific fuel consumption.

As a result of these differences, different types of engines will be developed for each sector. Military engines will take the form of low-bypass ratio turbofan engines or perhaps variable cycle engines that operate as turbofans at low speeds, but operate as turbojets at high, supersonic, velocities. These engines can meet military requirements for thrust while simultaneously satisfying requirements for aircraft stealth and supersonic capability. Commercial engines, on the other hand, will take the form of large high bypass ratio turbofans and possibly propfans which offer significant reductions in SFC. The military has little interest in such engines except for its larger transport aircraft, so the military is unlikely to fund development of new engines for such aircraft. New commercial engines will be suitable to their needs. As a result, less direct commercialization of military engines will occur in the future.

Despite differences on the product level, some commonality will remain between military and commercial engine cores and the basic technology incorporated into these cores. As was demonstrated, future military bomber engines may be designed with smaller, more powerful cores than those in present engines. These cores could have potential for powering commercial high-bypass ratio turbofans, allowing some transfer of core technology. In addition, much of the basic research conducted by the military will be applicable to commercial needs. Both military and commercial engines can further benefit from additional increases in engine turbine inlet temperature and compression ratio. Thus, military research in high-temperature materials and compressor stage design will be of use in commercial engines as well. In general, the more efficient engine components being developed by the military will be applicable to commercial engines as well.

Not all areas of research required for further development of commercial engines will be addressed by military programs. For example, research in advanced nacelle design for ultra high bypass turbofans and research on advanced fan blade design for commercial propfans are unlikely to be adequately addressed by current or future military research programs such as IHPTET. Thus, the commercial industry will have to bear more of the burden of its engine research and development costs.

B. Policy Implications

These conclusions imply that the commercial jet aircraft engine industry can expect a decline in the amount of technology transferred from military research and development programs. In addition, the decline in defense procurement referred to in Chapter I threatens to reduce the military contribution to the industry's capital base. At the same time as military sources of funding are declining, international competition in the aircraft engine industry is growing. Foreign engine makers are developing engines that may prove to be competitive with those of U.S. manufacturers. Both Rolls-Royce and Germany's MTU have ultra-high bypass ratio engines currently under development that may compete with the GE90 and the Pratt & Whitney ADF engines (Gray and Conliffe, 1990, p. 35). French, Japanese, and Italian engine manufacturers are also gaining experience in engine design through collaboration with GE, Pratt, and others.

These trends imply that funding for commercially-oriented engine R&D in the U.S. will have to rise in order to maintain the technological superiority and competitiveness of the U.S. commercial jet aircraft engine industry. Although jet engine technology has matured significantly over the past five decades, commercially significant improvements are still achievable. With advances in turbine inlet temperature, compressor design, and nacelle design, turbofan engines can be developed with significantly greater thrust and lower fuel consumption than current engines (Glassman, 1989; Newton, 1985; Mordoff, 1982). Propfan engines promise even greater reductions in fuel consumption.

The significance of the U.S. jet engine industry to the U.S. economy, national security, and national prestige demands that policies be developed to help preserve the nation's lead in jet engine technology. The large risks and high cost associated with jet engine development may well require continued or additional government involvement in this industry. Both government and industry actions should be directed toward enhancing the capabilities of the U.S. jet engine industry in an environment of declining military influence. Directions for commercial research must be developed and means for funding such research must be sought. Several guidelines for developing appropriate policies for achieving these goals are provided below.

1. Directions for Military and Commercial Jet Engine Research:

The most direct implication of the research contained in this thesis concerns the directions for future military and commercial jet engine research. As was demonstrated in Chapter V, both military and commercial engines can benefit from advances in high-temperature materials, lightweight materials, compressor design, and component efficiency. Military development work can then focus on incorporating the results of this research into low bypass or variable-cycle engines. Commercial development can focus on incorporating this research into ultra-high bypass turbofan engines. Development of ultra-high bypass engines and propfans for commercial application will require additional research into advanced nacelle design and blade aerodynamics, areas in which the military has limited interest.

These results suggest research priorities for industry and for government sponsors such as the Department of Defense and NASA. Assuming military funding for jet engine research will continue to outstrip civilian funding of aeronautical R&D[1] (regardless of the military's budget for <u>procurement</u> of engines), funding of commercial research by industry and by NASA should be directed toward problems such as fan blade aerodynamics and nacelle design that are peculiar to commercial engines and will not be addressed by military research. Advances in materials, compressor design, and component efficiencies should be developed by the military and transferred to the commercial industry. In this manner, the totality of research funds can provide the greatest benefit to commercial engine manufacturers.

The military should continue to fund development of improved engine cores through research in materials, compressors, and component efficiencies. In addition, opportunities for developing commercially-applicable technologies should be sought in military programs. In determining whether to design a new engine for a military aircraft or to modify existing engines, consideration should be given to the application newly-developed technologies may have to the commercial industry. Such considerations are especially applicable in the case of bomber engines which are likely to retain more commonality with commercial engines than are fighter engines.

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[1]According to AIAA estimates, Department of Defense budget outlays for aeronautical R&D in 1988 were almost nine times greater those from NASA during the same year (AIAA, 1990).

2. Improving Technology Transfer Mechanisms:

Central to the success of the strategy outlined above will be the ability to transfer technology from military research programs to commercial development programs. As technology transfer becomes characterized more by the transfer of research results and process innovations between industry sectors than by the direct commercialization of military engines, the knowledge to be transferred between research and development groups will become more tacit. As Teece (1981) has demonstrated, tacit knowledge, by definition, is difficult to articulate, so transfer is difficult unless those who possess the knowledge can demonstrate it to others. New structures may be necessary in order to maximize communication between differing R&D agencies and companies. Stronger attempts will need to be made by laboratories conducting engine research to disseminate research results to engine manufacturers and by corporations involved in military R&D work to disseminate information regarding advances in military engine design to commercial engine design groups.

Industry has begun to respond to the change in technology transfer by reorganizing so as to maximize the potential for transfer. Pratt & Whitney, while maintaining separate corporate divisions for the development of commercial and government engines, now uses a centralized Engineering Division to conduct basic research in areas such as advanced materials that can be applied to both development divisions. In addition, engines from both development divisions are produced by a single manufacturing division located in East Hartford. While security restrictions may impede the sharing of production lines for military and commercial engine programs, knowledge regarding production and manufacture may be transferred by sharing production personnel.

Likewise, General Electric, though divided into two development facilities, uses a single Advanced Technology division to conduct research applicable to both military and commercial engines. GE's plants are not divided into military and commercial development and production centers, but rather are distinguished by technical capabilities. Thus, military and commercial variants of an engine are designed and produced at the same facility, again enhancing prospects for technology transfer.

These changes in corporate structure tend to improve <u>internal</u> technology transfer <u>within</u> a corporation; additional mechanisms may be needed to more efficiently transfer technological know-how from government research centers to U.S. engine developers. To date, American aerospace manufacturers lag their European competitors in applying the results of NASA research to new aircraft and engine products (March, 1990, p. 33). These competitors actively collect and evaluate technical aeronautical data published in the U.S. and successfully use this data in the design of their products (NAS/NRC, 1985, p. 139). U.S. aerospace manufacturers less actively integrate NASA research results into their development programs. As successful transfer of research results from military programs to commercial programs is necessary for improving commercial aircraft engine design, greater emphasis should be placed on developing adequate means of transferring research results from government programs to industrial engine producers.

3. Funding For Subsonic Propulsion Research:

In order to maintain the competitiveness of the U.S. jet aircraft engine industry, additional sources of funding may have to be tapped to finance commercial research and development programs. At present NASA appears to be the only government agency with sufficient resources and a suitable charter to coordinate such research (NAS/NRC, 1985, p. 135). Under the National Aeronautics and Space (NAS) Act of 1958, NASA was chartered to "preserv[e] the role of the United States as a leader in aeronautical science and technology. . . ." (NAS/NRC, 1981, p. 37). NASA has historically emphasized the development of space technology at the expense of subsonic aeronautical technology. According to figures published by the Aerospace Industries Association of America (AIAA, 1990), NASA budget authority for aeronautical research and technology represented only 8% of NASA's R&D budget for 1990 and only 3.7% of its total budget for fiscal year 1990. These figures are characteristic of NASA's past budget allocations. NASA has historically devoted the majority of its budget to space programs; in light of the changing environment in the commercial aviation industry, these priorities may need to be reevaluated.

The need for additional funding of subsonic aviation research appears justified. As this and other reports (Glassman, 1989; Newton, 1985) have demonstrated, considerable potential exists for the continued development of commercial gas turbine engines. With advances in compressor design, turbine inlet temperature, advanced nacelle design, and fan blade aerodynamics, considerable reductions in SFC and hence in aircraft direct operating costs can be gained from gas turbine engines. High bypass turbofan engines will most likely remain the backbone of the commercial aviation industry. Propfan technology, an evolution of the gas turbine engine, also has applicability to commercial aviation. U.S. leadership in jet engine technology could translate into direct economic benefit to the nation. Sales of aircraft engines and spare parts by U.S. manufacturers totalled over fifteen billion dollars worldwide in 1989; roughly two-thirds of these sales were to customers other than the U.S. government (AIAA, 1990, p. 28). Total commercial engine sales are expected to remain high in the near future despite reductions in military sales (Aviation Week, 1991b, p. 88). By retaining its technological superiority and global competitiveness, the U.S. engine industry and the U.S. economy in general have much to benefit from such prospects.

4. NASA's Role in Engine Validation:

The 1985 report issued by the National Academy of Sciences and National Research Council (NAS/NRC, 1985) called for a greater involvement of NASA in the validation of subsonic engine technologies. Validation is the process whereby new technologies are tested under representative flight conditions so that manufacturers may better understand means to incorporate the innovation into a product. Validation helps a manufacturer determine the likelihood of a new technology being certified by the Federal Aviation Administration (FAA); it thus helps reduce the risk associated with later product development. At present NASA is involved primarily in the research phase of engine development; validation is left up to the developers. Yet, because most new engine technologies have historically been developed first for military application, the military has funded most of the validation costs.

The analysis contained in this thesis supports the Academy's recommendation. As was shown in Chapter III, the military has played a vital role in validating technologies for commercial industry. The high-bypass turbofan engines developed by Pratt & Whitney and GE were derived from military engines. As military and commercial technologies diverge, however, the amount of commercial technology validated by the military can be expected to decline. Unless additional funding can be found for commercial validation, industries may not be able to afford this part of engine development. Validation costs are high due to the large amount of testing that must be conducted on a new technology. For example, GE anticipates that it would require over four years and 1.3 billion dollars to certify its UDF engine (Taylor, 1990).

The burden on commercial industry could be eased by expanding NASA's activities to include validation. As the Academy report notes, validation activities are within NASA's charter. The technologies studied during validation are generic, not particular to a design under development; thus, the results of such tests are helpful to all competitors in an industry. Additional research may be needed to more fully explore the potential of this proposal.

5. Industrial Collaboration:

Another means of enhancing the ability of the U.S. jet aircraft engine industry to conduct large scale research programs despite the declining military budget would be to encourage collaboration between companies engaged in engine research and development. By pooling resources in a precompetitive research program, new technologies could be developed for later incorporation into products. As much of the technology such as high temperature materials needed for continued advancements in jet engines is generic, collaboration in basic research may provide a means of developing new technologies without sponsoring new products.

The greatest risk associated with such a strategy may be the potential loss of participants' proprietary data. However, the Department of Defense often claims the rights to new materials and technologies anyway and disseminates applicable fabrication and manufacturing techniques to other organizations (Kandebo, 1987, p. 59). Thus, the additional risk associated with direct collaboration may be outweighed by the benefits of larger available resource pools. Clearly, though, additional research is required in this area to determine whether such a scheme would be feasible in practice.

6. Market Strategies:

The government can also play a role in creating a stronger market pull for new engine technologies, thereby providing greater assurance to engine developers that their investments in new technology development may generate a return. The government, in particular the FAA, could increase demand for new engines by establishing stricter requirements for safety, noise, emissions, or fuel efficiency of aircraft. As military procurement decreases, the industrial base for engine manufacturing may decline unless commercial orders can fill the gap. Government regulation could stimulate commercial demand for engines.

The effects of deregulation have reduced the technology pull formerly exerted by commercial airlines on the engine manufacturers (March, 1990, p. 30). Many airlines are hesitant to invest in new technologies unless they can be proven to improve profits regardless of improvements in performance. In addition, the destabilization of route structures brought about by deregulation has weakened airline desire to make 20-year fleet commitments on new aircraft and engines. As a result, demand for new aircraft has decreased. Airlines appear satisfied to continue using older, yet proven technology (Markillie, 1988, p. 21).

Government regulations regarding aircraft safety, noise, emissions, and fuel-efficiency could provide the added incentive to restore some of the lost technology pull to the engine industry. As the MIT Commission on Industrial Productivity notes, airlines are now replacing their aging fleets due in part to the enforcement of Stage 3 noise regulations that older aircraft cannot meet (MIT, 1989, p. 51). Though designed to address problems of environmental concern, these regulations have also served to increase demand for aircraft and engines. By phasing in these regulations over time, the burden placed upon the airlines was reduced to an acceptable level. The apparent success of this approach suggests that additional regulation could stimulate market pull in other areas such as fuel efficiency as well.

Such a policy would not be without drawbacks. Undoubtedly, the costs of purchasing new engines would be passed on to the consumer in the form of higher fares and as a result demand for air travel could decline. Depending upon the price elasticity of demand for air transport, the resulting loss in demand for air travel could outweigh the benefits to the commercial engine manufacturers. Further research will be needed in this area in order to fully characterize the types of regulation possible and their likely effects on the economy as a whole. Yet, this type of policy has the potential to restore the demand for new engine technologies.

7. Increased Globalization of Commercial Engine R&D:

The reduction in technology transfer from the military will likely stimulate further globalization of commercial engine development programs. At present, both major U.S. engine manufacturers are involved in multi-national partnerships. GE co-developed and is co-producing the CFM-56 engine with SNECMA of France. Pratt & Whitney is a partner in International Aero Engines, a consortium comprised of Rolls-Royce, Japanese Aero Engines, MTU, and Fiat Aviazione. These partnerships allow U.S. manufacturers to share the risk of large development projects, to gain access to foreign markets which are often oriented toward purchasing domestic products, and to gain access to alternative sources of capital (MIT, 1989, p. 10).

As military funding declines and becomes less suited to the development of commercial engines, U.S. manufacturers will have increased incentive to seek international partners who have access to alternative sources of funding and are willing to accept development risk in order to strengthen their position in the aircraft engine market. This trend will raise additional questions regarding the transfer of U.S. technology to foreign competitors--questions which have implications for both national competitiveness and national security. To date, both GE and Pratt have arranged their partnerships so as to retain control of core technologies which are controlled by U.S. export regulations. However as a recent report by the National Academy of Sciences has stated, the increasing globalization of the aircraft industry "has attendant negative implications for control by any single nation of the export of production technology" (NAS/NRC, 1991, p. 226). Strong export controls present an impediment to multinational collaboration. In order to participate in future collaborative efforts and remain competitive in the global market, U.S. export control measure may need to be relaxed.

Export control could be further relaxed without jeopardizing U.S. leadership in jet engine technology. Present laws control export of engine cores. As this thesis demonstrates, advances in jet engine design will derive from developments in materials and their processing. The important technology that should be protected is not, therefore, the engine itself, or even the engine core, but the combined knowledge of the materials design and fabrication processes. Product superiority is based not upon the acquisition of a single technique or associated product, but on the integration of design, materials processing, and manufacturing processes

(NAS/NRC, 1991, p. 230). Thus, export controls that allow the sale and transfer of completed engines and components, but do not allow sharing of production or processing technology could protect U.S. interests in security and technological superiority while simultaneously enhancing the ability of U.S. engine manufacturers to participate in multinational development programs.

C. A Final Word

The discussion presented in this chapter demonstrates the effect that the growing divergence between military and commercial engines may have on the U.S. jet aircraft engine industry and upon the formulation of policy to maintain the competitiveness of the industry. As military and commercial technologies diverge, research priorities will have to be redirected and additional financing will have to be secured. Means for achieving these goals may require the reconsideration of NASA priorities regarding aeronautics, the expansion of NASA's activities to include technology validation, the development of new structures to foster communications between firms and to stimulate collaborative research, and the reconsideration of U.S. export control laws.

The conclusions of this research should, however, be considered only in light of the many other factors, political, economic, and technological, that may influence the competitiveness of the aircraft industry as a whole or that may affect other industries and policies. The close ties between the engine industry and the airframe manufacturing industry cannot be overlooked in policy development or in setting goals for the aircraft engine industry. Hopefully, the discussion contained in this thesis will not only provide guidance applicable to the U.S jet aircraft engine industry, but will also help to identify areas of further interest to be researched in studying the rest of the U.S. commercial aircraft industry. By properly understanding the trends characterizing the development of the industry and developing policies to appropriately respond to these changes, the success of the U.S. aircraft industry can be better assured.

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