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Multiple Application Core Engine: Sizing and Usage Criteria

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Significant aircraft and propulsion system life-cycle cost savings may be realized by designing, developing, and maturing an advanced technology engine core (high-pressure rotor) for multiple application in a number of different aircraft types. Should the concept of a multiple application core engine (MACE) be proven feasible, common core development can be started separately from the aircraft system in a low-risk program free from flight test milestone pressure. Such a program would enable early durability testing of high temperature components with attendant earlier engine maturity and improved operational readiness. Each successive engine derived from this common core could be developed at significant cost savings compared to a completely new engine. This paper documents a study conducted at Pratt & Whitney Aircraft during 1978-1979 in which several turbojet and turbofan engines were configured around a common core design by adapting appropriate fans and/or low-pressure compressors. Core sizing and usage criteria are discussed along with preliminary but encouraging airframe contractor application analyses which indicate that a more detailed investigation of the MACE concept is warranted.

Introduction

ACQUISITION and operating costs of Navy weapon systems have climbed so high that the service can no longer afford to replace all aircraft being lost or worn out. The 1980 defense budget calls for buying only 39 Navy tactical aircraft, significantly short of the 180 planes required annually to maintain 12 carrier task groups and three Marine air wings through the 1980's (Fig. 1). The cumulative shortfall for the Navy will be in excess of 200 aircraft by the end of 1979. The Air Force is faced with a similar procurement problem. In an era of diminished defense budgets and high inflation rates, system life-cycle cost must be drastically reduced so that funds can be made available to procure sufficient numbers of new systems. Clearly, a new development philosophy is required, not only to reduce development and acquisition costs of new systems, but also to attack the high ownership costs of those systems after they become operational.

Several new types of high performance aircraft will be required by the services to meet the advanced threat of the 1990's. However, development of an all new, unique propulsion system for each new aircraft type would present insurmountable cost and scheduling problems for the Government. On the other hand, development time and risk could be reduced, improved durability and earlier maturity achieved, and development cost reduced by as much as 60% if a single common core (high-speed rotor consisting of high-pressure compressor, combustor, and high-pressure turbine) could be used for a number of engine applications by adding the appropriate fans and/or low compressors to provide the desired engine operating characteristics.

The multiple application core engine (MACE) promises significant benefits relative to the reduction of weapon system life-cycle cost. First and foremost, if the core can be sufficiently common to a number of different types of aircraft, its development can be started early, even prior to selection of the first aircraft system for which that core is to be used. Such decoupling of core engine and weapon system development programs could provide a unique opportunity to carry out intensive development testing and durability demonstration of critical hot section components early in the development cycle, with attendant earlier maturity of the engine. Further, the lower risk development program, possible because of the absence of system flight test milestone pressure, would enable a significantly larger transfusion of advanced technology into the core and engine designs. The larger technology bite could directly impact life-cycle cost by improving performance and durability, while at the same time reducing complexity and numbers of parts. Finally, though perhaps most obvious, are the derived savings from commonality of parts. If, for example, a core design is common to two or more types of aircraft, subsequent application of this fully developed and mature core could provide significant development cost savings, depending on the complexity of the low rotor configuration to be added.

In view of the potential life-cycle cost savings, this paper will examine the concept of a multiple application core engine by addressing the following key questions. First, can a single core size be found to meet a number of diverse aircraft applications without incurring large penalties in system weight and performance? Second, can a core be developed for multiple usage in fighter, bomber, attack, and trainer environments with acceptable balance of weight, performance, durability, and reliability?

History of Propulsion Development

During the 1950's and 1960's, most new aircraft were designed around an existing engine or core. The same basic engine was used to propel fighters, attack aircraft, bombers, military transports, commercial transports, and high-altitude surveillance aircraft. Modifications for specific applications, such as the addition of an afterburner for fighters or a high bypass ratio fan for a transport, were made as necessary, but the same basic propulsion system was used for all applications with few differences in the high-pressure spool. For example, the Pratt & Whitney Aircraft (P&WA) J57 engine, developed for the B-52 bomber, was reconfigured into the TF33 and JT3D by adapting a new low spool to the basic J57 core. The J57 family of engines powered 14 different aircraft including B-52 and B-66 bombers, F100, F101, and F102 century series

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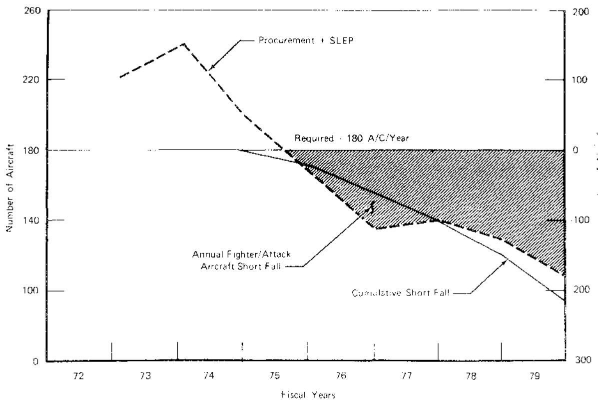

Fig. 1 USN/USMC fighter aircraft, required vs available.

fighters, Navy F4D and F8U fighters, KC-135 tankers, the U-2 surveillance airplane, and B707 and DC8 commercial transports. Some compromise in ultimate aircraft performance probably resulted from this common use and engine parts life differed from application to application, but these effects were relatively minor and the practice was highly cost effective.

In the past decade, the performance complexity and sophistication of new weapon systems increased dramatically, resulting in more and more specialized usage of systems for different tasks. Different engine duty cycles were required for different aircraft types and the compromises made to use a given propulsion system in a number of applications became much greater. Optimum engine size and cycle depended upon such factors as aircraft range and payload, specific mission definition, and energy maneuverability requirements. Optimum bypass ratio and overall engine-pressure ratio greatly differed for the fighter and bomber applications.

The engine designed for the modern bomber with its sustained steady-state operation was deemed unsuitable in the fighter environment which demands a significant amount of operating time at or near maximum turbine temperature and a large number of severe, rapid throttle transients. Application of the bomber engine to a fighter aircraft required considerable redesign and development testing of the bomber engine core at the conditions representative of the fighter aircraft environment. The same was true, to a somewhat lesser extent, of the engine designed for the fighter aircraft environment and subsequently used in a bomber application. As a result, it became generally accepted that a common powerplant for multi-usage was no longer practical and that development of a new engine should not be started until the weapon system requirements were firmly defined and an engine cycle optimized for that specific use. Most recently, new procurement programs, such as the F-15, B-1, and F-18 followed this practice.

However, as pointed out in the introduction, a brand new engine developed simultaneously with each new weapon system is not a practical solution. This approach is no longer affordable. Also, the concurrent development approach practiced during the past decade introduced new problems because the propulsion system, which could not be started prior to complete definition of the weapon system, required a year longer to qualify for flight test than the aircraft. Because of milestone pressure, durability testing was necessarily limited. Consequently, the real durability evaluations occurred only after the system entered operational service, where it was subjected to severe and prolonged stresses and thermal cycles. Durability problems severely impacted operational readiness and "fixes" were incorporated via expensive and time-consuming component improvement programs. Thus, the advantage of being able to design to the specific aircraft requirements in the concurrent development approach was offset by the limited durability testing forced by system milestone pressure. The problems of concurrent development were further aggravated by the adverse feedback loop into the propulsion system that required "turning up the wick" (forcing the engine to operate at higher and higher combustor temperatures) to compensate for system performance deficiencies or weight increases that evolve during the development process. The aforementioned problems of the concurrent development approach are significant contributors to the high cost of ownership of systems in service today.

A better approach (economically) might be to develop a common or multiapplication core, suitable for both the bomber and fighter aircraft environments, by designing to the maximum limits of the fighter/bomber composite duty cycle. Fighter and bomber engines can then be constructed from this core by selecting low spools for each engine that provide the optimum bypass ratio (for turbofans) and overall pressure ratio. This approach appears feasible from a development standpoint, provided that the core is designed and tested for the worst duty cycle mix and the resulting bomber and fighter engines are extensively tested at their respective duty cycles. Only relatively minor compromises, primarily in weight, should result from this approach.

Our backward glance into history allows us to conclude that improved durability, earlier maturity, and lower cost of ownership can be achieved by increasing emphasis on environmental testing of core and engine early in the development cycle. The multiple application core engine approach appears to offer the best opportunity ever to accomplish this early durability testing, since development of a core common to several applications can be initiated prior to weapon system selection.

MACE: An Attractive Alternative

The multiple application core engine (MACE) envisioned would have an "essentially" common (though not necessarily identical) high-speed rotor consisting of high-pressure compressor, combustor, and high-pressure turbine. For purposes of this discussion, a common or multiple application core is defined as one designed for the composite fighter/bomber duty cycle and whose allowable physical differences are sufficiently small that the core need not be redeveloped to demonstrate durability of hot section components. The following guidelines are consistent with this definition: 1) the addition or deletion of a single compression stage while maintaining essentially the same compressor exit corrected flow, 2) minor variations in turbine flow area (accommodated through vane class or other selective assembly techniques) and 3) different variable inlet guide vane or compressor stator schedules.

A family of turbojet and turbofan engines is derived from this common core by combining with low-speed rotors having various combinations of fan and/or low-pressure compressors.

By adding the appropriate low-pressure spool, the same engine core can be used to configure either subsonic, high bypass ratio engines having excellent cruise and loiter fuel consumption, or supersonic afterburning engines with very high thrust-to-weight ratios. An example of the versatility of an advanced technology common engine core as just defined is shown in Fig. 2. This core was arbitrarily sized for 55 lb/s compressor inlet corrected flow, a pressure ratio of 7.5, and 2800°F combustor exit temperature. By adding a single front supercharging stage to the core compressor, a simple 7-9000-lb thrust (augmented) single spool turbojet engine can be configured for a supersonic tactical aircraft or trainer. Replacing the supercharging stage with a small diameter, multistage low-pressure spool doubles thrust and provides a turbojet engine for supersonic V/STOL B or CTOL applications. A slightly larger fan further increases thrust in a low bypass ratio (0.6-0.8) turbofan engine for a supersonic

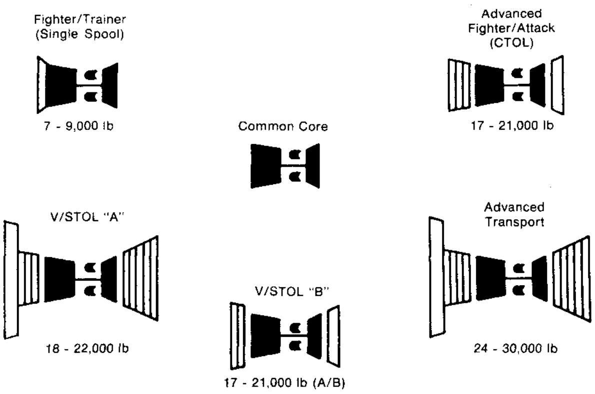

Fig. 2 One core—many applications.

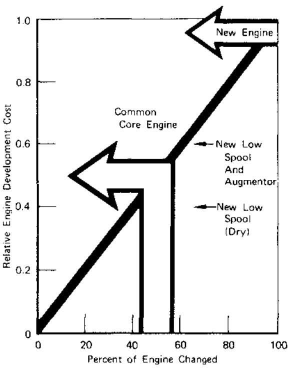

Fig. 3 Derivative engines reduce development cost.

V/STOL B application. By significantly increasing fan size and also adding a multistage low compressor, a high bypass ratio (4-6) advanced turbofan engine of up to 30,000-lb thrust can be configured for transport applications. Further increasing fan size provides a very high bypass ratio (8-12) turbofan engine for the V/STOL A application.

Obviously, all the engines derived from this core will not be optimized for each application. However, it will be shown later that the compromise does not appear to penalize aircraft capability significantly, whereas the life-cycle cost savings could be very large.

Advantages of the MACE Concept

The most apparent advantage of a multiple application core engine, mentioned in the introduction, lies in the potential for very large development, acquisition, and ownership cost savings. These savings are achieved through greater part commonality for a number of engines; particularly those parts comprising the core or high-pressure spool. Core parts normally operate at the highest temperatures, pressures, and rotational speeds, and dictate the capability of the entire engine. They also dictate the pace and cost of the development program and determine to a large extent the durability levels to be achieved by the engine. Significant cost and schedule savings can be realized by subsequent application of a fully developed and mature multiple-usage core to a new aircraft system. Figure 3 shows the proportional relationship between the percentage of engine change and relative engine development cost, with a totally new engine representing 1.0 on the relative development cost scale. It can be seen that the cost to develop a dry or nonaugmented engine, based on an existing core and new low-pressure spool, represents a little over 40% of the cost to develop an entirely new engine. This figure could reach 60% with a new low-pressure spool and augmentor. The cost to simply add a "zero" stage to the existing core would be less than the 40% figure, though somewhat greater than the cost of engine uprating. Thus, it appears possible that each subsequent usage of a common core would provide development cost savings of up to 60% for each application compared to the cost of a totally new engine.

Acquisition and ownership cost savings likewise accrue from part commonality. Acquisition savings result from increased volume production of parts common to a number of engines. Ownership cost savings accrue from the reduced cost of spare parts (volume production), the standardization of maintenance procedures, interchangeability, and simplified logistics network achievable with more common parts in the inventory.

Although the potential cost savings achievable from greater part commonality should not be minimized, the more important advantage of the multiple application core engine derives from the improved development approach possible. The core, common to a number of weapon systems, can begin development early; even prior to weapon system selection. Separated from the usual milestone pressure that accompanies simultaneous development of engine and weapon system, more emphasis can be placed on core endurance and accelerated mission testing to demonstrate reliability and durability goals. The ability to place increased emphasis on durability testing early in the development cycle will allow even the first engine derived from the common core to achieve earlier operational maturity. Early maturity will reduce the normally high required funding outlay for component improvement programs and expensive retrofit programs. These dollar savings alone could be enormous. Subsequent applications of the common core will carry forward the levels of core maturity attained in prior applications with increased levels of confidence and further reductions in operational costs.

Another important advantage also derives from the ability to start development of the core early. By starting early in a reduced risk effort, the core program provides a unique vehicle for transition of new technology defined in independent or Government-funded programs (such as advanced turbine engine gas generator and joint technology demonstrator engine programs). Because of the reduced risk and pressure, a larger, directed technology step is possible, offering the best opportunity ever to attain a better balance between performance, weight, cost, reliability, maintainability, and durability in production engines.

Obviously, a price must be paid to realize these advantages. A common core engine of necessity cannot be optimally sized for every application. Also, a common core must be designed for a composite duty cycle encompassing the limits of usage of several types of aircraft (i.e., fighters, bombers, transports, trainers, etc.). At the same time, differences in the core must be sufficiently minimized to avoid the need for redevelopment. It is necessary then to determine the magnitude of any penalties/compromises in aircraft capability, takeoff gross weight (TOGW), and life-cycle cost imposed by core commonality; and to balance any cost decrement against the potential cost savings previously described to arrive at the overall financial benefit of the MACE concept. The remainder of this paper will address this issue by presenting results of a cooperative P&WA/aircraft industry study of the MACE concept completed in early 1979. The study was designed to assess concept feasibility by investigating the payoffs and penalties associated with common core sizing and usage.

Core Size

In order to assess the viability of selecting a single core size for a number of advanced aircraft, several U.S. airframe contractors joined with Pratt & Whitney Aircraft for the independent core sizing study. P&WA supplied these participating airframers with data packages for a family of six study engines derived from a common core having a base corrected compressor exit flow of approximately 5.6 lb/s, scaleable to 150%. Airframers compared the "best" common core engine from the data provided with the optimum engine for each of several advanced aircraft types currently under study to determine: 1) what applications could be grouped with a single core size, and 2) what penalties were paid in TOGW or other mission parameters to accommodate core commonality. Airframers also were to determine what applications could not be satisfied within the scaling range of the basic core provided and/or to determine what other sizes would be of interest.

The basic core size selected for the study was determined using a market forecast of advanced military aircraft becoming operational in the early 1990's and beyond. Figure 4 shows the projected market in numbers of engines as a function of thrust class, considering the various tactical and strategic aircraft that could make up the total future defense inventory. Helicopters and other aircraft requiring very small engines were omitted to minimize the scope of the study. In this forecast, no attempt was made to determine whether fighters would be single or twin engine aircraft; both were assumed. Likewise, two, three and four engine bombers and transports were assumed. The intent was to look at the market for all potential types and configurations to determine areas of maximum interest.

Next, the market was segregated by aircraft type and engine cycle (Fig. 5). Here it was assumed (based on practical experience) that transport/bomber engines would tend toward relatively high bypass ratios (BPR ~ 6) with overall pressure ratios ranging between 24 and 32. Large fighters would have low bypass ratios of about 0.8 with overall pressure ratios between 20 and 28, while small fighters and trainers would tend toward "leaky" or straight turbojets at overall pressure ratios between 8 and 16.

A baseline core size, defined by corrected compressor exit flow, was then estimated by preparing a carpet plot of thrust as a function of that parameter for each of the four aircraft types, using the bypass ratios and overall pressure ratios just defined (Fig. 6). Corrected compressor exit flow was the logical basis for sizing the core since it was determined that a nearly constant turbine flow parameter should be maintained to avoid the complication, weight penalty, and potential durability problems of a variable area turbine.

The following procedure was used to generate Fig. 6. Starting with the transport/bomber configuration, by holding constant the overall pressure ratio of 32:1 (the upper limit), thrust was scaled as a function of corrected compressor exit flow. The same was done at an overall pressure ratio of 24:1 (the lower limit), thus generating an operating band for the strategic type aircraft. By superimposing the thrust limits from the market forecast, the desired operating range becomes bounded. The same procedure was followed for the other three cycles of interest to determine if there would be a value of corrected compressor exit flow common to the different aircraft types. If so, a common hot section for these applications is feasible.

A range of exit flow between 5 and 7 lb/s intersects the bounded areas of all aircraft types except the small nonaugmented fighter engines. For these, a compressor exit flow of about 10 lb/s would be more desirable. Recognizing that there may be as many as three or four core sizes required to completely cover all aircraft and rotorcraft of interest, a family of study engines was derived from a base core having a corrected flow of about 5.6 lb/s by adding the appropriate low-pressure spools. Each of the engines in the family is defined in Fig. 7 by bypass ratio and by both dry and augmented thrust. A data package was prepared for each

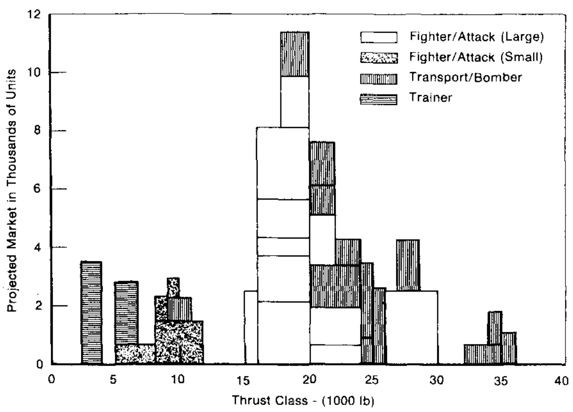

Fig. 4 Post-1985 forecast of military aircraft engines.

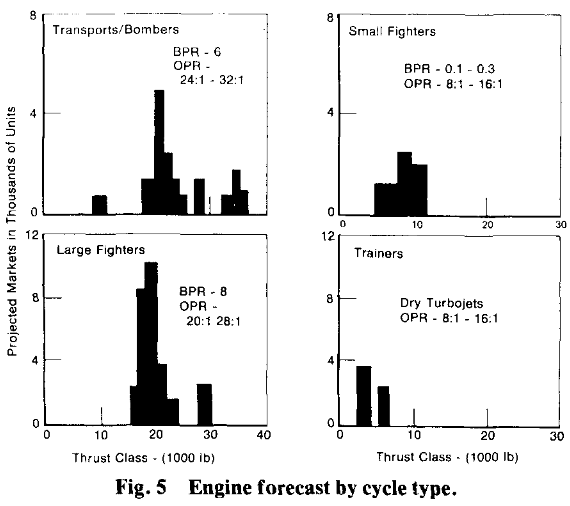

Fig. 5 Engine forecast by cycle type.

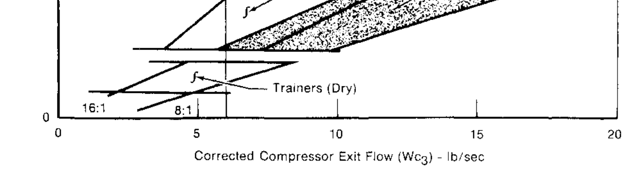

Fig. 6 Core size for multiple applications.

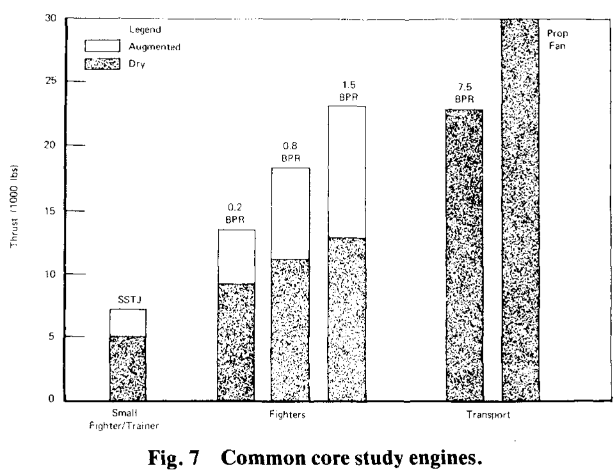

Fig. 7 Common core study engines.

Table 1 Core differences

	Fighter/ Trainer[a] SSTJ	0.2 BPR	Fighter/Attack 0.8 BPR	1.5 BPR	Transport/Bomber 7.5 BPR	Prop fan
Compressor stages	+1	−1	Base	Base	Base	+1
Turbine area	112%	100%	100%	100%	103%	100%
Combustor exit temperature	2800	2800	2800	2800	2507	2450
Overall pressure ratio	13	25	25	25	30	30

[a] Design point: Sea Level Static (SLS) for fighters, cruise for transports.

study engine, which included basic installation data, weights, and performance. These data packages were provided to all participating airframers.

The differences in the common core for this family of study engines, for the most part, fall within our definition of "common" previously given. The differences are summarized in Table 1. Note that for the mini-study, the design point for fighters was at sea level static conditions; whereas, bombers and transports were designed at altitude cruise conditions. A "zero" stage was added to the base high-pressure compressor to provide a 13:1 pressure ratio single spool turbojet for small fighter/trainer application (5000 lb of thrust dry, 7000 lb augmented). Only in this application did the turbine area fall outside of what was considered desirable limits for a fixed core engine design. However, the additional development required for the larger area high-pressure turbine is deemed acceptable in the case of a single spool turbojet where no low-pressure rotor is required. The 103% turbine area of the transport engine (BPR = 7.5) is considered to be within the limits of turbine vane classes or selective assembly techniques. Overall, the core differences are considered minimal, especially since no real effort was expended to try and reduce these differences through cycle matching techniques.

Four airframe contractors presented data for a total of ten aircraft sized around the family of common core study engines. Aircraft types studied included cannon fighters, V/STOL and STOL fighters, advanced tactical fighters, supercruisers, and a subsonic bomber. Results were quite remarkable. First, all airframers concluded that several applications could be tailored around the family of common core study engines with minimum penalties in TOGW, compared to the optimum engine for each configuration (where both the common core and optimum engines were equivalent in technology level). The maximum penalty in TOGW for any of the ten aircraft studied, using the base core size without optimization, was less than 10%. By adjusting bypass ratios and throttle ratios and scaling the core 115-120% above the base core size, the maximum TOGW penalty for any of the ten applications appears to fall below 5%. The trend is encouraging.

A second, unexpected result observed in the data was that for the same ten applications, TOGW was relatively insensitive to changes in core size over a wide range of core sizes, when bypass ratio was simultaneously changed to maintain the overall thrust requirement. This result was observed by plotting trend curves for each of the ten applications, showing how TOGW changed as core size was varied. A composite of these trend curves is shown in Fig. 8, where it is seen that the maximum all-cause penalty in TOGW can be brought within 10% for any of the applications by adjusting core size. Since the study engines and aircraft were not optimized because of the necessarily limited scope of work, penalties in TOGW occurred that were not the sole result of core size (such as nonoptimized cycles, installation effects, throttle ratio, etc.). In order to view the impact on TOGW of core size alone, the trend curves were normalized to a null or zero TOGW penalty by eliminating all engine-caused influences other than core size. The normalized curves are shown in Fig. 9, with each application reaching the null or

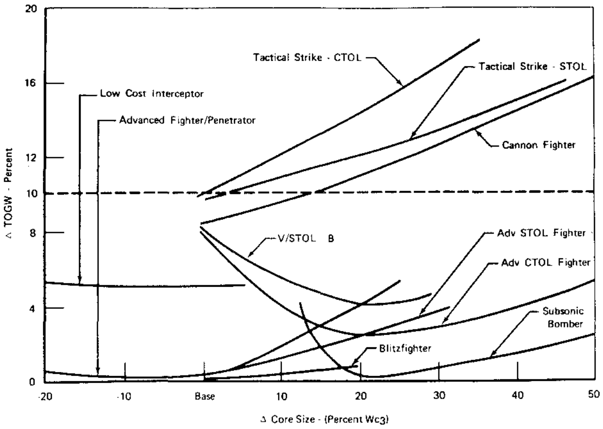

Fig. 8 Nonoptimized study results.

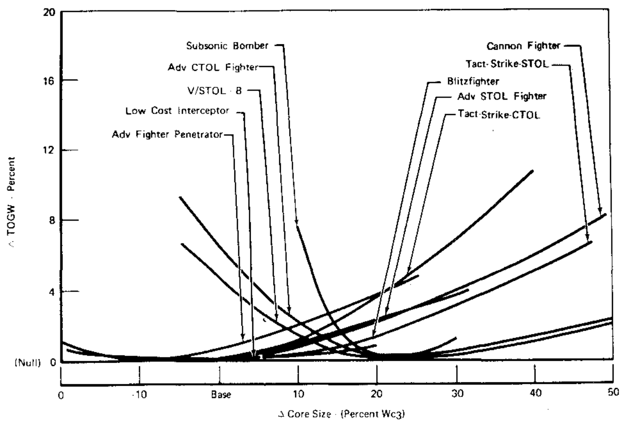

Fig. 9 Normalized study results.

zero TOGW penalty at its optimum core size. It can be seen that the optimum core sizes varied from about 10% below to about 35% above the baseline core provided (5.6 lb/s corrected compressor exit flow). Also obvious is the fact that each of the applications exhibits a rather small variation in TOGW for rather large swings in core size. This is particularly true in the region to the right of the null point for each application where the core is basically oversized. The implication is that if the core is generally large enough to produce the required thrust at low to moderate bypass ratios, the partial derivative of TOGW with respect to core size is relatively small. Note that ΔTOGW increases to the right of the null point because of increased specific fuel consumption at lower bypass ratios that accompany larger core sizes; reflecting added fuel requirements for a constant mission. If the core is basically too small as depicted by that area to the left of the null for each application, the required thrust must be achieved by using large bypass ratios and the penalties due to excessive nacelle drag become a driving influence.

Boundaries defined by the upper limits of ΔTOGW for the composite of the ten trend curves shown in Fig. 9 provide: 1)

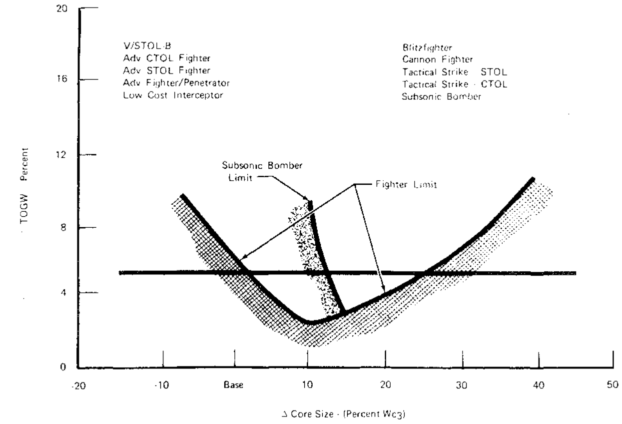

Fig. 10 One core—ten applications

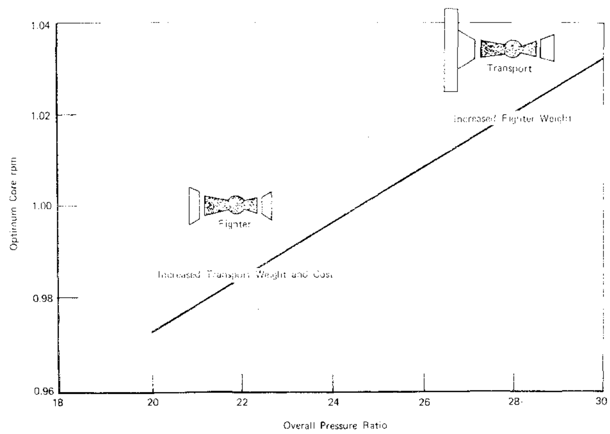

Fig. 11 Mechanical speed considerations

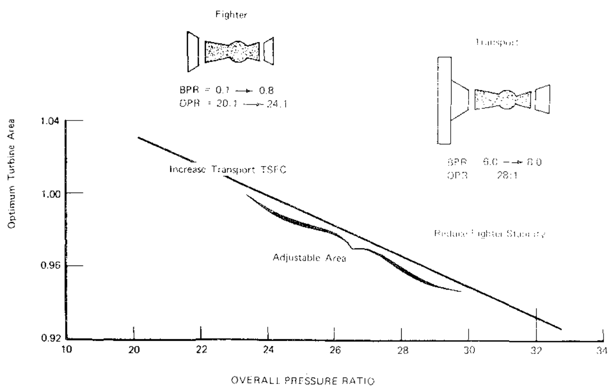

Fig. 12 Component matching considerations

the bounded ΔTOGW profile for all nine fighters, and 2) the bounded profile for all ten aircraft, including the subsonic bomber. These boundaries describe the impact on TOGW for worst case of the aggregate of ten applications as core size was varied from base (Fig. 10). For the nine fighter applications, the worst case variation in TOGW was 5% or less over a 24% range of core size and under 8% for nearly 40% change in core size.

While absolute values are subject to question, nonetheless the trends are significant, indicating that it may not be necessary to pinpoint an exact core size prior to initiating a core development program. If this is true, core development can be started before selecting the first application, since nominal variations in size will not inflict serious weight penalties on the system. Further, the core could be intentionally oversized at the onset of development to compensate for anticipated weapon system growth without imposing a significant weight penalty.

A third conclusion was that the base core size picked for the study turned out to be within 15-20% of the optimum size for which airframe contractors found a number of potential applications. Other sizes of interest were identified but not further explored due to the limited scope of the study. Considerably more analysis will be required before drawing any final conclusions, but the results to date are encouraging relative to finding a single core size that will satisfy a number of future aircraft applications.

Core Usage

Equally important with finding the optimum common core size is determination of the multiple usage of that core in bomber or fighter aircraft environments. Two basic questions to be addressed are: 1) Can a composite duty cycle be established that will truly represent the usage of a multiple application core engine in the real operational environments of several different types of military aircraft? 2) What are the compromises in design and the penalties in core weight and performance compared to an optimum engine when designed for a composite duty cycle?

In attempting to answer these questions, the designer must first consider some of the fundamental differences in the bomber and fighter engine requirements. Although the bomber and fighter aircraft both operate over the same range of altitudes and Mach numbers (and thus the same range of inlet temperatures and pressures), there could be many differences that drive the designs of the two propulsion systems. For the bomber or transport engine, heavy emphasis is placed on long-range cruise performance, and low thrust specific fuel consumption is a primary design objective. The fighter, on the other hand, is essentially a transient machine designed for violent maneuvering; and primary objectives are high thrust-to-weight ratio, tolerance to severe throttle excursions, and engine stability.

Because of the requirement for good cruise performance, the transport or bomber engine is designed for higher bypass ratios and higher overall pressure ratios than the fighter engine. If the two engines have a common core, the transport or bomber engine will need to generate more pressure ratio in the fan and low compressor stages to achieve the higher overall pressure ratio. Thus, the absolute values of temperature and pressure at the high compressor inlet will be higher. With higher inlet temperature, the bomber or transport high spool must operate at a higher rotational speed in order to maintain a constant value of corrected speed ($N/\sqrt{T}$). The effect is shown in Fig. 11. If one were to design the common core at the higher rpm of the transport engine, the fighter core would have to be designed for higher than necessary disk loads with resulting weight penalty. If, on the other hand, one were to design the common core at the lower rpm of the fighter engine, more stages of low compressor might be required to achieve the higher overall pressure ratio of the transport or bomber engine, with resultant penalties in weight and cost. It could be argued that these differences are minimal if the fighter is required to operate at higher Mach numbers than the bomber (higher inlet temperatures), or if the increased weight of fighter engine high-pressure turbine disks is required anyway for improved durability. Nevertheless, these kinds of differences must be considered at the onset of the common core design.

By following a similar line of reasoning, it can be deduced that the bomber or transport engine, because of its higher overall pressure ratio, optimizes at a lower turbine area than the fighter engine (Fig. 12). If the common core is designed to the lower turbine area of the transport engine, to maintain fighter engine thrust the operating line on the fighter engine compressor map must be raised, resulting in reduced stability margin. If, on the other hand, the common core is designed for the higher turbine area of the fighter engine, the operating line on the transport engine compressor map will be

Table 2 Common core life criteria

	Fighter/Trainer Training	V/STOL B/ATF	Military transport	Tanker
A/C design life, yr	20	20	25	25
Utilization				
h/mo	33	33	42	42
h/flt	1.6	1.7	1.5	4.0
LCF cycles				
Type I	5000	4800	10,000	3750
Type III	45,000	22,100	0	0
Engine design life, h	8000	8000	15,000	15,000

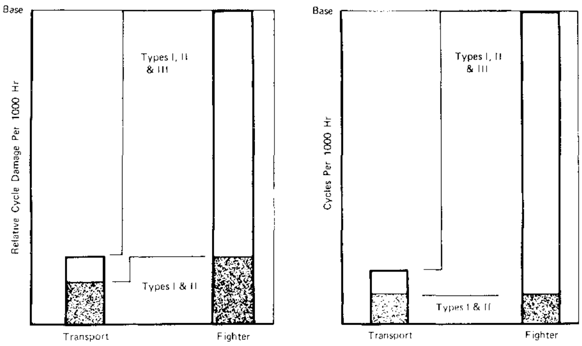

Fig. 13 Typical cyclic use.

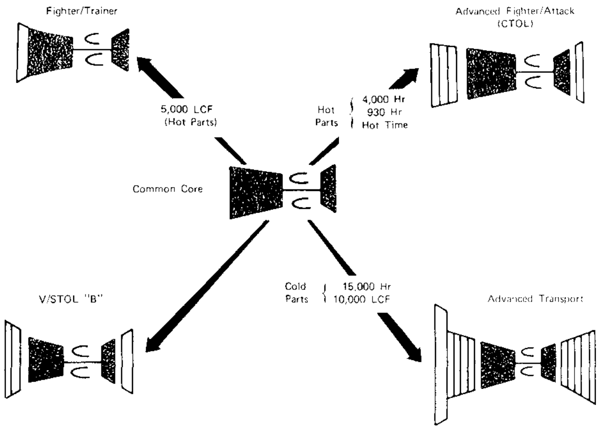

Fig. 14 Equivalent worst case duty cycle.

depressed, resulting in reduced efficiency and Thrust Specific Fuel Consumption (TSFC) penalty. Here again, one could argue that if the transport engine is designed for the altitude cruise condition and the fighter engine designed for sea level static, differences in optimum turbine area could be minimal; certainly within the range that could be accommodated by selective turbine vane classes at assembly. Nevertheless, the initial design must account for these fundamental differences.

Perhaps the biggest difference in usage between the fighter and bomber is in the cyclic operation of the two engines as a function of time. Figure 13 shows the dramatic difference in number of cycles per 1000 hr and cyclic induced damage per 1000 hr for the two engines. Type I and type II cycles represent engine start-up to maximum thrust and shutdown (type I at sea level static conditions and type II at high Mach numbers). Type III cycles represent throttle transients from idle to maximum thrust and back to idle. It is obvious from the figure that the fighter engine experiences a significantly larger number of type III cycles over a given period of time than the transport engine. At first glance, this would appear to place more severe structural requirements on the fighter engine. However, when one considers that the life of the bomber or transport is two or three times longer than that of the fighter, and that the type III cycles are less damaging than type I cycles, it could be that the cyclic induced damage incurred over the life of the two systems may not be all that different from a design standpoint.

The objective here is not to argue one way or the other relative to the degree of differences in usage between bomber/transport and fighter engines, but rather to show that the anticipated differences, whatever they may be, must be considered from the onset of the common core engine design.

In considering core design for multiple application, it is important to recognize that there are two types of operation that are the major contributors to reduced engine part life. These are: 1) time at near rated turbine temperature and flight speeds, and 2) throttle excursions from start or idle to maximum rated thrust. These two types of operation cause different kinds of distress, resulting in hardware life reduction. Prolonged running at high temperatures, pressures, and speeds induce such distress mechanisms as 1) compressor and turbine disk creep and growth, 2) combustion chamber wall overheating and burning, 3) turbine airfoil creep, 4) turbine airfoil burning and erosion, 5) augmentor liner distress, and 6) exhaust nozzle liner and flap burning. Large numbers of severe throttle transients, on the other hand, can lead to problems such as 1) compressor stator vane cracks, 2) compressor and turbine seal spacer cracks, 3) compressor and turbine disk stress rupture, 4) turbine airfoil fatigue cracks, 5) burner wall fatigue cracks, and 6) augmentor liner and exhaust nozzle fatigue cracks. Therefore, a necessary prelude to initiating design of a multiple application core engine will be the extensive analysis of future system requirements along with the missions, flight envelopes, and duty cycles of the tactical and strategic aircraft needed to meet those requirements. Only from such analysis can a composite duty cycle be established that will realistically encompass the combined usage of all engines derived from the common core.

For the evaluation of usage impacts on common core engine design reported herein, a composite duty cycle was estimated by selecting the "worst case" components of the individual duty cycles for the aircraft types shown in Table 2. This table represents an estimate by Pratt & Whitney Aircraft of anticipated life criteria for future tactical and strategic aircraft based on data assembled to date for typical aircraft now in the inventory. Now, if it is assumed that engine cold parts are required to last the entire life of the aircraft system and hot parts one-half of system life (probably representative of durability goals for next generation aircraft), the worst case equivalent duty cycle for the common core can be defined as shown on Fig. 14. It can be seen that hot part life is limited by: 1) the 4000 total operating hours (half of system life) of the advanced fighter aircraft, of which 930 h are anticipated to be at maximum temperature; and 2) the 5000 Low Cycle Fatigue (LCF) cycles of the small fighter/trainer aircraft. The latter was derived by finding the total type I cycles (in terms of damaging effect) for the assumed 4000-h hot section life of the trainer aircraft. Cold part life is limited by the 15,000 total hours and 10,000 LCF cycles of the advanced transport. If a

Table 3 Multiple usage penalty fighter application

Core weight	+12% (54 lb)
Engine weight	+3.4%
TSFC	+0.8%
TOGW	+2.5% (1080 lb)

single core is to be designed for all of the above applications with the assumed life limiting criteria of Fig. 14, two questions arise: 1) Which engine or engines would be penalized relative to an optimized engine in any given application? 2) What is the extent of the penalties?

The surprising conclusion from the above simplistic example was that the biggest design drivers were the total life and LCF cycles of the bomber or transport which dictated the design of the cold parts. Thus, cold parts of the fighter are somewhat overdesigned because of the bomber or transport life requirements. The penalties for the fighter engine, shown in Table 3, result in only 2.5% increase in TOGW and 0.8% increase in TSFC. These penalties are not considered excessive in terms of the potential life cycle cost benefits of a multiple application core. Here again, the mini-study results are encouraging and point toward the feasibility of the multiple application core approach.

One final note relative to usage. To this point, we stressed design criteria. However, of equal importance is the development and qualification for operational use. Testing must reflect the duty cycle that the engine will be subjected to by the user. Core testing must include the limits of the worst case duty cycle, accurately duplicating operational power settings and throttle excursions. Fighter and bomber engines utilizing the common core must be tested to the fighter and bomber duty cycles, respectively, including steady state and transient testing at the correct simulated flight conditions.

Conclusions

A multiple application core engine promises large potential development, acquisition, and ownership cost savings to the Government for future advanced tactical and strategic aircraft. If common to a number of systems, the core can be developed separately and in advance of aircraft development, eliminating much of the risk caused by milestone pressure typical of a concurrent development program. The lower risk program would provide an excellent opportunity to transition advanced technology into new propulsion systems, resulting in greatly enhanced performance and improved durability. Most important, however, the ability to start core development prior to and apart from system development would allow early and extensive durability testing of critical hot section components, promising earlier maturity of the engine. Direct and indirect cost savings of the common core approach could be large.

A multiapplication core engine is not a new idea. An examination of aviation history shows that a great majority of past aircraft were designed around a common engine or core. The approach was both mission and cost effective. Although sophistication of weapon systems has resulted in more specialized usage, recent studies indicate that a common core may be designed to the composite worst case duty cycle of several systems with very small penalties to any of the included aircraft. Preliminary study results also indicate that a core can be sized to fit a number of aircraft applications with small penalties, since TOGW appears to be relatively insensitive to core size over a wide range of core size if bypass ratio is varied accordingly to maintain the thrust requirement.

The results are far from conclusive, but the trends identified are encouraging. Greater depth of study is warranted to determine:

1) The minimum number of engine core sizes that will satisfy a majority of aircraft types required by the services through the year 2000.

2) The real penalties to systems due to the multiapplication core approach and impact on overall effectiveness.

3) The total life-cycle cost savings possible, using the common core engine approach compared to the optimum engine approach.

4) The design, test, and evaluation criteria to be used in the development of a common core engine.

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