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Development of Engines for Unmanned Air Vehicles: Some Factors To Be Considered

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INSTITUTE FOR DEFENSE ANALYSES

IDA Document D-2788

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J. Richard Nelson, Project Leader
Donald M. Dix

Preface

The Institute for Defense Analyses (IDA) prepared this document for the Office of the Director, Strategic and Tactical Systems under a task titled "Tactical Air Warfare Programs Technical and Schedule Risk Assessments." The objective of the task is to provide data, information, and methods for assessing schedule and technical risks associated with major acquisition programs in preparation for milestone reviews to aid in Defense Acquisition Board decisions. This document partially fulfills that objective by providing an assessment of potential needs in engine or technology development for unmanned air vehicle (UAV) applications.

William S. Hong of IDA was the technical reviewer for this document.

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Summary

Purpose and Scope

This brief study resulted from a desire by the Office of the Under Secretary of Defense (Acquisition, Technology and Logistics)/Strategic and Tactical Systems (OUSD(AT&L)/S&TS) to obtain an independent assessment of potential needs in engine development or technology development for unmanned air vehicle (UAV) applications, with particular emphasis on potential differences between UAV engines and manned aircraft engines.

The objectives of the study were to:

- examine the similarities and differences between potential UAV power plant requirements and those of manned aircraft;
- identify any needs in either technology development or engine development that may be unique or of particular importance to UAVs; and
- recommend any actions appropriate to ensuring the availability of capable engines for UAVs.

The scope of the investigation was largely focused on the gas turbine as the power plant of interest. Accordingly, emphasis here is on UAV applications for which the gas turbine is a candidate power plant. In general, these applications require greater than 100 pounds of thrust or 100 horsepower at takeoff.

Approach

The approach used consists of the five following elements.

1. Assess potential UAV applications to ascertain likely mission needs, projected quantities, thrust or power levels required, and similarities to and differences from manned aircraft.
2. Estimate the benefits and costs of new or derivative engines, as compared to the use of existing engines, with emphasis on the magnitude of improvements in engine characteristics needed to justify engine development.
3. Assess the availability and suitability of existing engines for UAV applications, in terms of output level and performance characteristics.

4. Evaluate technical and managerial considerations that may be unique or of particular importance to UAV engines.
5. Examine the prospects for UAV applications of two unconventional engine types, the fuel cell and the pulse-detonation engine.

Findings

Potential UAV Applications

We explored two of three identifiable classes of UAV applications:

- Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) UAVs—these aircraft are characterized by medium or long range and/or endurance, medium to high altitude, medium to high subsonic speeds, and sensor and communication payloads. Global Hawk is an example of a high-altitude, long-endurance C4ISR UAV.
- Combat UAVs—these aircraft are characterized by medium range and endurance, medium altitude, medium and high subsonic speeds, and weapons payloads. The Air Force Unmanned Combat Air Vehicle (UCAV) and the Navy UCAV are illustrative of current exploratory systems.

This study disregarded the third class—battlefield UAVs such as Pioneer and Shadow—because it represents relatively small UAVs for which gas-turbine engines are not candidate propulsion systems.

The majority of Department of Defense (DoD) efforts (Global Hawk, Air Force UCAV, and Navy UCAV) are for vehicles in the 20,000- to 30,000-pound class. More generally, it appears that long-range C4ISR and combat UAVs will be only slightly smaller than manned aircraft that perform similar missions; hence, they could ultimately exceed 30,000 pounds gross weight. In any case, these aircraft will be neither inexpensive nor expendable.

Gas-turbine engines are candidate propulsion systems for C4ISR UAVs, combat UAVs, and virtually all rotorcraft UAVs. Power requirements may range from 100 pounds of thrust or horsepower to perhaps 15,000 pounds of thrust or higher, with the higher values (7,500–15,000 pounds) more likely. These power requirements span the range of those for cruise missiles to those for medium-size aircraft.

Four characteristics other than the size of UAVs may influence the propulsion system. First, endurance in UAVs is likely to be greater than that in manned aircraft for similar missions, because C4ISR UAVs will not be limited by human endurance, and combat UAVs will have a surveillance and reconnaissance role of some sort. Second, the operational usage may be different than that of manned aircraft—including storage of UAVs until needed in combat—that may result in shorter life requirements. Third, power extraction from the engine for operation of both the payload and vehicle may be a significantly higher fraction of engine power than in manned aircraft. Finally, combat UAVs may be low-signature designs, which influence engine installation and airflow.

Projected procurement quantities for UAVs are difficult to estimate. If the DoD decides to use UAVs to perform missions currently performed by manned aircraft, and uses them is substantial numbers, then a single UAV model could be procured in relatively large numbers, perhaps in the 500–1,000 range (e.g., the DoD currently has about 2,700 fixed-wing aircraft primarily devoted to ground attack). The potential market for UAVs would then be similar to the historical one for manned aircraft. Current DoD UAV acquisition programs, however, reflect an approach to UAVs that has a significant exploratory component and limited procurement quantities—on the order of 100 or less of a single model. This uncertainty in procurement quantities has a significant influence on the nature of engine development.

Benefits and Costs of Engines

The benefits and costs of engines as applied to UAVs, in conjunction with the number likely to be procured, are significant factors in the approach taken for engine development or modification. Large benefits, low costs, and large procurement numbers favor the development of new engines for UAV applications; small benefits, high costs, and low procurement numbers favor minor adaptations of existing engines for UAV applications.

The benefits of engines are measured by their impact on the costs of aircraft systems. Lighter weight, more fuel-efficient engines permit either smaller, less-expensive aircraft for a given mission or greater mission capability at no increase in aircraft size and cost. Lower cost engines—in procurement and operation and maintenance—reduce the cost of the aircraft system by the amount of engine cost reduction. The cost of achieving such benefits is the development cost of the engine. Based on an analysis of four notional UAVs—one long-range C4ISR UAV, and three UCAVs, our findings (from Chapter 3) are:

- Thrust specific fuel consumption (TSFC) is by far the most influential engine characteristic in determining benefits, weight/thrust ratio is the second most influential, and engine procurement cost is the least influential.

- These sensitivities to engine characteristics are similar to those for manned aircraft performing similar missions, except that TSFC is somewhat more influential and thrust/weight ratio is somewhat less influential in UCAVs than in attack aircraft. From the standpoint of technology development, this implies that technology goals suitable for engines for manned aircraft are also suitable for UAVs, with perhaps more emphasis on TSFC reduction.
- A relatively large system buy and a substantial improvement in TSFC (as compared to an existing engine) will be required to justify the development cost of a new engine—increases in thrust/weight ratio alone are not likely to be adequate. If we assume that fleet procurement cost savings should be about 3 times the development cost of an engine to justify the investment, a system buy for a typical UCAV on the order of 1,500 would be required for a new engine with a weight/thrust ratio improvement of 40 percent. If a TSFC improvement of 20 percent can also be obtained, then the required buy reduces to about 750 systems. The corollary to this observation is that if system buys reach this magnitude, then the benefits of a new engine are substantial.
- The development of derivative engines may be easier to justify, depending upon the situation. For example, the development cost of replacing the fan of an existing engine may be only 10 percent of the development cost of a new engine; lesser engine improvements and system buys could justify such a modification.

Availability and Adaptability of Existing Engines for UAVs

Obviously, the availability and adaptability of existing engines is a significant consideration for UAV applications. The three factors of most importance are: (1) the available thrust or power level; (2) the suitability of engine characteristics, most notably TSFC; and (3) any special considerations for UAVs that might render an otherwise satisfactory engine unsuitable. With respect to the first two factors, the findings (from Chapter 4) are:

- From the standpoint of thrust or power level only, the spectrum of UAV needs is adequately covered. There are ample turbine engines available, provided that the requirements of any prospective air vehicle are adjusted to match a specific engine.
- For long-range C4ISR applications, it is likely that existing (or new) transport engines can be adapted with minor modifications. Low TSFC is paramount in these applications, and the preferred engines are accordingly high-bypass-ratio, low-specific-thrust turbofans—engines favored by both small and large transport aircraft.

- For UCAV applications, it is likely that significantly modified engines, or possibly a new engine will be required. The tradeoff between TSFC and signature control indicates that medium by-pass-ratio, medium-specific-thrust engines will be favored, and there do not appear to be any existing engines with satisfactory characteristics.

Special Considerations for UAVs

The first-order characteristics of engines—thrust, weight, specific fuel consumption, and cost—are obviously major considerations in UAV applications. There are, however, other factors to be considered. These factors are broadly of the two following types: (1) technical matters concerning engine design features or operating characteristics that may be important in UAV applications and might also render an existing engine unsuitable for UAV applications and (2) management matters concerning engine development and qualification.

Four technical areas that may require special treatment in UAV engines are: (1) power extraction; (2) high-altitude effects; (3) potential long-term storage requirements; and (4) performance-life-cost tradeoffs. The central finding with regard to these factors (from Chapter 5, Section A) is that none are likely to provide sufficient cause for the development of a new engine or, with the possible exception of power extraction, a significantly modified engine.

With regard to engine development, the situation is different for C4ISR applications than for UCAV applications. For C4ISR applications, the findings (from Chapter 5, Section B) are:

- For applications beyond Global Hawk, it will be important to match the characteristics of the air vehicle to the availability of existing engines; an air vehicle that requires a new engine is unlikely to be developed. It will also be important to consider potential growth requirements, since any growth in engine thrust must be accompanied by a proportional increase in airflow to maintain constant specific thrust and a low TSFC.
- Modifications for significant power extraction, however, could be extensive, and arriving at a cost-effective solution will require tradeoffs between engine performance, cost of the modifications, and air vehicle performance and cost.

In contrast to C4ISR applications, UCAV applications will require at least one engine that is more than a minor modification of an existing engine. Before initiating a major engine development effort—derivative or new—four related questions will need to be addressed:

- Could a common engine (or modest variants of a common engine) satisfy the requirements for both the Air Force and Navy UCAVs? The current similarity in size and thrust requirements of Air Force and Navy versions suggests that minor adjustments to perceived mission requirements could make a common engine possible.
- What is the appropriate magnitude of engine development? The possibilities range from developing a new fan for an existing core and low-pressure turbine to developing an all-new engine. The choice here involves several factors: what the manufacturers can offer; the cost of the development; the effect on the cost-effectiveness of the system(s); and the number of engines likely to be procured.
- Shall the engine be contracted for as government-furnished equipment (GFE) or contractor-furnished equipment (CFE)? If a common or "almost common" engine is practical, then engine development would be best contracted for as GFE. If an engine is unique to one air vehicle, then treating it as CFE is practical, but may not be the optimal way to obtain the necessary degree of attention to engine development.
- What should be the timing and nature of engine development programs? The historical practice of initiating a complete engine development program when the air vehicle program is fully defined may not be suitable, given the current fluid state of perceived UCAV requirements. This suggests the possibility of initiating a "limited" engine development—development to the point of initial flight release and fabrication of a few engines—with no commitment to proceed further.

The optimum answers to these questions are not obvious; arriving at a suitable course of action requires a thorough examination by the interested parties. Such an examination would be timely.

With regard to qualification requirements, the formulation of a new generic specification for UAV engines is not recommended. Existing generic specifications are adequate, and since UAVs are neither inexpensive nor expendable, it is unlikely they can be relaxed significantly. Nonetheless, the costs of qualification of UAV engines may be reduced by attention to three areas (from Chapter 5 Section B.2):

- *Definition of the quantitative requirements.* Some UAVs may have (1) a less demanding operational envelope than, say, attack aircraft, (2) lesser life requirements, and (3) somewhat more tolerance for maintenance. Appropriate specification of these requirements will reduce the amount and nature of developmental testing required.

- *Consideration of continued or spiral development.* If the spiral development approach is being followed, it may be possible to reduce the initial life, durability, and reliability requirements of an engine, and hence the amount of developmental testing required.
- *Verification by similarity for derivative engines.* If a UAV engine is a derivative of an existing engine, then the verification of some requirements may be possible by similarity, with perhaps some additional analysis, as opposed to developmental testing.

All three of these areas are engine- and program-specific. It is not possible to find a universal solution for all engines and all programs, but careful attention and perhaps negotiation at the outset of a program should produce a cost-effective development.

Unconventional Engine Candidates

The essential findings resulting from the assessment of fuel cells and pulse-detonation engines (PDEs) for UAV applications (from Chapter 6) are:

- Fuel cell power plants are not a significant consideration for the UAV applications considered here, due to the significant increase in power density that will be required. At best, fuel cells may eventually offer advantages for extremely long-endurance missions; but the number of vehicles likely to be required for such missions is small, and, hence, fuel cell power plants would need more widespread application to justify their development.
- PDEs are also not a significant consideration for the UAV applications considered here. The stand-alone PDE is not suited for subsonic UAVs because the specific fuel consumption is much higher than that of a gas-turbine engine. The other possibility is to use a pulse-detonation device as the high-pressure element of a gas-turbine engine; development of such a compound engine is, at best, far in the future, and would need to be developed for an application more widespread than UAVs.

Recommendation

Before any commitment is made about engine development for UCAV applications, OUSD(AT&L)/S&TS should ensure that questions are addressed about the possibility of a common Navy-Air Force engine, the magnitude of the development, the method of contracting, and the timing and nature of the development program.

I. Introduction

A. Background

The increased emphasis on larger unmanned air vehicles (UAVs) for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) and for weapon-delivery purposes raises some potential issues related to their propulsion systems. To date, as might be expected for the limited quantities of C4ISR aircraft involved, minor modifications of existing gas-turbine engines have been used as power plants. These modifications have thus far primarily addressed operation at higher altitudes than those for which the original engine was designed. In the longer term, however, the prospect of larger quantities and a weapon-delivery role will, at a minimum, lead to more significant modifications of existing engines, and may require an approach that addresses the differences between UAV power plants and those for manned aircraft more specifically. These differences include: the desirable trade-offs among performance, cost, and life/durability; operational usages (e.g., perhaps long periods of non-use for some types of UAV power plants); relatively higher power extraction demands on UAV engines; the smaller size of some types of UAV engines; and the potentially increased prospects for unconventional power plants in UAVs. This brief study responds to a desire by the Office of the Under Secretary of Defense (Acquisition, Technology and Logistics)/Strategic and Tactical Systems (OUSD(AT&L)/S&TS) for an assessment of these potential differences.

B. Purpose and Scope

The objectives of the study were to:

- examine the similarities and differences between potential UAV power plant requirements and those of manned aircraft;
- identify any needs in either technology development or power plant development that are unique or of particular importance to UAVs; and
- recommend whatever actions, if any, appear appropriate to ensure the availability of capable power plants for UAVs.

The scope of the investigation is largely focused on the gas turbine as the power plant of interest. Accordingly, emphasis here is on UAV applications for which the gas turbine is a candidate power plant. In general, these applications require greater than 100 pounds of thrust or 100 horsepower at takeoff, approximately.

C. Approach

The approach followed here consists of the following five elements: (1) assessment of potential UAV applications, including mission needs and projected quantities; (2) analysis of the benefits and costs of new engines, as compared to the use of existing or derivative engines; (3) assessment of the availability and suitability of existing engines; (4) evaluation of technical and managerial considerations that may be unique or of particular importance to UAV engines; and (5) assessment of the prospects for unconventional engines.

The primary aims of identifying potential UAV applications (Chapter 2) are to establish the general thrust levels that may be needed, estimate the potential quantities involved, and identify mission needs to the extent that they influence desired characteristics of the propulsion system. This is accomplished by reviewing information both in the public domain and provided by the engine manufacturers. These results form the basis for estimating the benefits and costs of new or modified engines (in Chapter 3). The relative importance of various engine characteristics—specific fuel consumption, output/weight ratio, and procurement cost, specifically—is obtained by defining notional UAV characteristics and using a simple model to determine the sensitivity of vehicle characteristics to changes in engine characteristics of interest. These sensitivities provide insight into the potential impact of engine improvements, and are used as the basis for comparing the benefits of an engine with the costs of developing or modifying one.

The assessment of the availability and adaptability of existing engines in the output ranges of interest to UAVs (Chapter 4) is based on data obtained from both the engine manufacturers and information in the public domain. The general suitability of these engines to potential UAV applications is assessed on the basis of both available output and a comparison of actual characteristics with desirable characteristics for UAV engines. These results, in conjunction with those of Chapter 3, permit some inferences as to the nature of future UAV engine developments.

Technical and managerial considerations that may be unique or of particular importance to UAV engines (Chapter 5) have been identified on the basis of discussions with the engine manufacturers; these considerations are evaluated on the basis of their potential impact on UAV engine development, as well as their similarity to considerations for engines for manned aircraft.

Finally, the prospects for two unconventional power plants that may potentially be applicable to UAVs—the fuel cell and the pulse-detonation engine—are examined (Chapter 6) on the basis both of results achieved to date and projections for the future.

II. Potential UAV Applications

UAVs are not currently an appreciable part of the military force structure; hence, predictions of the nature and extent of the future force structure contain a high degree of uncertainty. Nonetheless, some bounds on the prospects for UAVs can be estimated on the bases of past and current activities, the missions to be performed, and the number of manned aircraft currently used to perform similar missions.

A. General Types of UAVs

Table 1 shows the overall characteristics of some UAVs in which the Department of Defense (DoD) has invested. For the purposes here, it is convenient to identify three categories of applications:

- *C4ISR.* The primary purpose of these aircraft is surveillance and reconnaissance. They are characterized by medium or long range and endurance, medium to high altitude, medium to high subsonic speeds, and sensor and communication payloads. Global Hawk is the current example of a long range/endurance, high-altitude C4ISR UAV; Predator is the current example of a medium range/endurance, medium-altitude C4ISR UAV.
- *Combat.* The primary purpose of these aircraft is to disable and/or destroy enemy targets. They are characterized by medium range and endurance, medium altitude, medium and higher subsonic speeds, and weapons payloads. The payloads can include ordnance of various sorts, directed energy weapons, and electronic warfare equipment. The DoD currently has no production or developmental systems in this category, but the Air Force and Navy Unmanned Combat Air Vehicles (UCAVs) are illustrative of exploratory systems.
- *Battlefield.* The primary purpose of these aircraft is also surveillance and reconnaissance. They are characterized by relatively short range and endurance, low to medium altitudes, low to medium subsonic speeds, and small sensor payloads. Pioneer and Shadow are representative of this class of UAVs.

Table 1. Overall Characteristics of Some DoD UAV Systems

System	TOGW (lb)	Payload (lb)	Radius (NM)/ Endurance (hr)	Ceiling (ft)	Thrust (lb) or Power (hp)
Production/Developmental					
RQ-1 Predator	2,300	450	400/24	25,000	113 hp
RQ-2 Pioneer	450	75	100/4	15,000	26 hp
RQ-4 Global Hawk	25,600	2,000	3,000/36	65,000	7,580 lb
RQ-5 Hunter	1,600	200	144/11	15,000	120 hp
RQ-7 Shadow	330	50	68/4	15,000	38 hp
Fire Scout	2,550	200	110/6	20,000	258 hp
Exploratory					
UCAV (AF)	~15,000	2,000	650/3	45,000	6,300 lb
UCAV (N)	~25,000	~2,000	~12 hr	~40,000	6,000–8,000 lb
Predator B	6,400+	~700	12–25 hr	50,000–60,000	750 hp/2,300 lb
MRE-Rotary Wing	~14,000	~1,000	~10 hr	~15,000	~2,000 hp
A-160	4,000	~400	~40 hr	~25,000	~500 hp

Sources: References [1 through 4].

Obviously, there are other ways to categorize UAV applications, but this categorization is suitable for examining propulsion system needs. The general power levels required are a strong function of takeoff gross weight (TOGW), and these are shown in Figure 1. Although the data are sparse, some inferences relevant to future propulsion system needs are possible:

- The battlefield UAVs are relatively small and generally require less than 100 horsepower or 100 pounds of thrust. The only vehicles that may exceed these power levels significantly are rotary-wing systems (e.g., Fire Scout). Since this study is largely focused on gas-turbine engines, little attention is given here to fixed-wing battlefield UAVs.
- The only UAV being considered with a takeoff gross weight in excess of 30,000 pounds is a rather vague concept called sensor craft, which could have a gross weight of perhaps 100,000 pounds. The majority of DoD efforts (Global Hawk and Air Force and Navy UCAVs) are for vehicles in the 20,000- to 30,000-pound class. More generally, it appears that long-range C4ISR and combat UAVs will be somewhat smaller than manned aircraft that perform similar missions. The size difference will likely be due to the desire for lower cost air vehicles, and the payload capacity may therefore be reduced. Other factors contributing to a somewhat smaller size are the absence of human beings in the aircraft, lesser thrust loading (TOGW/takeoff thrust), and fewer demands for vehicle acceleration capability. In any case, these aircraft will be similar in size and cost to manned aircraft that perform similar missions and will hence be neither inexpensive nor expendable.

- Gas-turbine engines are candidate propulsion systems for both C4ISR and combat UAVs, as well as virtually all rotorcraft UAVs. Power requirements may range from 100 pounds of thrust or horsepower to perhaps as high as 15,000 pounds of thrust. The upper limit is based on the assumptions that single-engine UAVs are unlikely to exceed 30,000 pounds TOGW and that the aircraft thrust loading (TOGW/takeoff thrust) is unlikely to be greater than 0.5. These power requirements span the range of those for cruise missiles and medium-size aircraft.
- None of the applications indicated in Figure 1 will require afterburning engines. The only foreseeable need for afterburning is for air-to-air UAVs, and these seem to be quite far in the future.

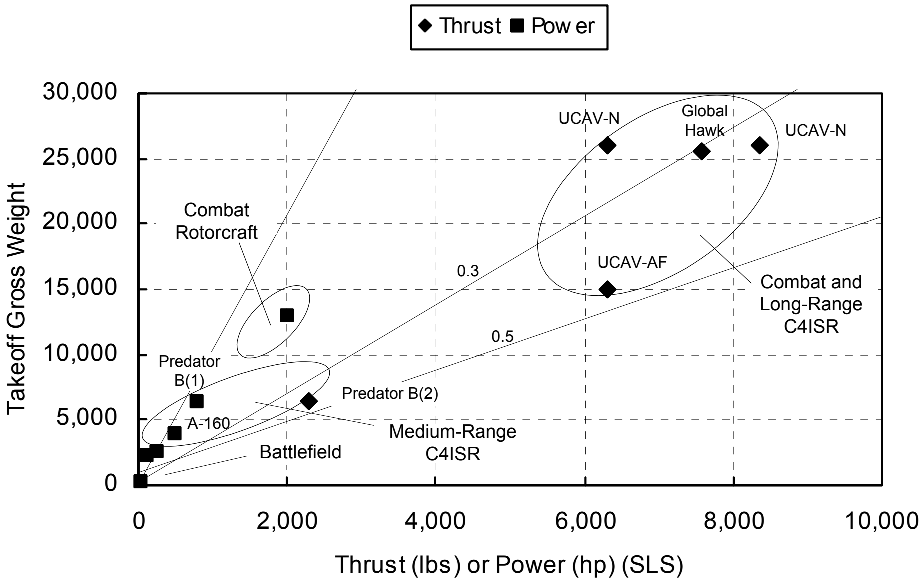

Figure 1. Power Ranges for UAVs

In summary, in terms of probable propulsive power requirements, UAV applications are consistent with previous manned-aircraft and cruise-missile applications.

There are four characteristics other than the size of UAVs that may influence the propulsion system. First, endurance in UAVs is likely to be greater than that in manned aircraft for similar missions, because C4ISR UAVs will not be limited by human endurance, and combat UAVs will have a surveillance and reconnaissance role of some sort. Second, the operational usage may be different than that of manned aircraft—including storage of UAVs until needed in combat—that may result in shorter life requirements. Third, power extraction from the engine for operation of both the payload and vehicle may be a significantly higher fraction of engine power than in manned aircraft. Fourth, combat UAVs may be low-signature designs, which influences engine installation and acceptable airflow. The influence of these characteristics on the propulsion system will be discussed subsequently.

B. Recent and Current DoD UAV Programs

A major factor, but not the only factor, in determining approaches to be taken for new or derivative engines for UAVs is the potential number of systems that will be part of the force structure. A reasonable place to begin in arriving at estimates is a review of past and current DoD efforts to develop and field such systems.

Table 2 shows a brief history of DoD UAV programs. Clearly, UAVs have thus far had a checkered history: several programs have been cancelled, the programs with the larger productions have been discontinued, and no systems have been acquired in particularly large numbers. There are no doubt rational explanations for this history, but they are not relevant here; the major point is that past history does not provide any basis for projecting future quantities.

Table 2. Recent DoD UAV Programs

System	IOC	Number Built	Number in Inventory	Planned
RQ-1 Predator	2001	54	15	87 ordered
RQ-2 Pioneer	1986	175	25	Discontinued
BQM-145	—	6	0	Cancelled
RQ-3 Dark Star	—	3	0	Cancelled
RQ-4 Global Hawk	2005	5	0	In E&MD
RQ-5 Hunter	—	72	42	Discontinued
Outrider	—	19	0	Cancelled
RQ-7 Shadow200	2003	8	0	176 planned
Fire Scout	2003	1	0	75 planned

Source: Reference [1], p. 3–9; as of December 2000.

Table 3 shows current DoD UAV acquisition programs. The investment plans are increasing substantially, both in procurement and in research, development, test, and evaluation (RDT&E), indicative of increasing emphasis on UAVs. The procurement quantities are modest, however, and the investment is heavily weighted toward RDT&E, indicative of an approach to UAVs that has a significant exploratory component. In any case, these shorter-term plans do not provide a basis for estimating future inventory levels.

Table 3. Current DoD UAV Acquisition Programs
(Millions of Then-Year Dollars)

	FY 2001	FY2002	FY2003
Procurement			
Global Hawk	21	117 (2)	171 (3)
Predator	30 (7)	244 (16)	154 (22)
Shadow	37 (4)	91 (9)	101 (12)
Subtotal	88	451	426
RDT&E			
Global Hawk (AF)	137	305	306
Global Hawk (Navy)	—	—	152
Predator	6	4	4
Shadow	34	38	47
Fire Scout	66	48	44
UCAV (Air Force/DARPA)	—	83	91
UCAV (Navy/DARPA)	28	42	50
Subtotal	271	520	693
Total	359	971	1,119

Source: Reference [5].
Note: Numbers in parentheses denote quantities.

C. Future Inventory Estimates

Table 4 summarizes the highest, lowest, and average estimates of potential procurement quantities for the next 10 years. U.S. engine manufacturers supplied the estimates, which the manufacturers said they had great difficulty in making. It is obvious from the range of estimates that the manufacturers are uncertain about the future market. The approximate DoD inventory of manned aircraft to perform similar missions is also shown in Table 4.[1] It is reasonable to infer that if the DoD decides to use UAVs to perform missions currently performed by manned aircraft, and uses them in substantial numbers, then a single UAV model could be procured in relatively large numbers (500–1,000). If this philosophy is adopted, then the potential market for UAVs is similar to, but somewhat smaller than, the historical one for manned aircraft. Currently, however, DoD efforts appear to be aimed at procuring rather limited quantities of a single model—on the order of 100 or less—and this uncertainty in procurement quantities has a significant influence on the nature of engine development.

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[1] C4ISR fixed-wing aircraft include the U-2, RC-135, E-3, P-3, E-2C, and S-3B; combat fixed-wing aircraft include the F-15E, F-16C/D, F-18, F-117, A-10, and AV-8; C4ISR rotary-wing aircraft include the OH-58A/C, SH-60, and UH-1; and combat rotary-wing aircraft include the OH58D, AH-1 and AH-64.

Table 4. Estimates of Future UAV Procurement
Contrasted to Current Manned Aircraft Inventory for Similar Missions

	Engine Manufacturer Estimates			DoD Aircraft Inventory
	High	Low	Average	
C4ISR—Fixed Wing	370	200	274	~500
Predator A	70	50	60	—
Predator B	50	50	50	—
Global Hawk	200	50	114	—
Sensor Craft	50	50	50	—
Combat—Fixed Wing	1,920	280	870	~2,700
Air Force UCAV	1,200	30	420	—
Navy UCAV	600	130	330	—
Multi-Role Endurance (MRE)	120	120	120	—
C4ISR—Rotary Wing	100	50	90	~600
Unmanned Reconnaissance, Surveillance and Target Acquisition Rotorcraft (URSTAR)/Fire Scout	100	50	90	—
Combat—Rotary Wing	100	50	75	~1,100
Unmanned Combat Armed Rotorcraft (UCAR)	100	50	75	—

III. Benefits and Costs of Engines

The benefits and costs of engines as applied to UAVs, in conjunction with the number likely to be procured, are a significant factor in the approach taken for engine development or modification. Large benefits, low costs, and large procurement numbers favor the development of new engines for UAV applications; small benefits, high costs, and low procurement numbers favor minor adaptations of existing engines for UAV applications. These benefits and costs are examined here. Other factors bearing on the approach to development—availability of existing engines and special considerations for UAV engines are discussed in subsequent sections.

The benefits of engines are measured by their effect on the costs of aircraft systems. There are two basic effects: (1) lighter weight, more fuel-efficient engines permit a smaller and less expensive aircraft for a given mission, or more mission capability at no increase in aircraft size and cost; and (2) lower-cost engines—in procurement and operation and maintenance—reduce the cost of the aircraft system by the amount of engine cost reduction. The first effect is obviously mission dependent. Missions demanding longer ranges reward reduction in specific fuel consumption, while missions demanding high aircraft thrust/weight ratios reward higher engine thrust/weight ratios. Stated another way, aircraft with higher fuel weight fractions place a premium on reduction in specific fuel consumption, and aircraft with higher engine weight fractions place a premium on increased thrust/weight (or power/weight) ratio. Fortunately, history provides some guidance on the likely distributions of these weights for various missions.

A. Representative Characteristics of UAVs

Table 5 shows the approximate weight distributions of some current developmental UAVs. It is instructive to compare these weight distributions to weight distributions of previous aircraft. In making this comparison, we used the development from Reference [6]. In brief, an aircraft is considered to consist of four weight elements: structure and subsystems, engine, fuel, and payload.[2] The sum of the last three elements is called the "available" weight. Reference [6] showed that the manner in which the available weight is distributed among its three constituents tends to be relatively invariant with time for aircraft with similar missions. Figure 2 displays the results.

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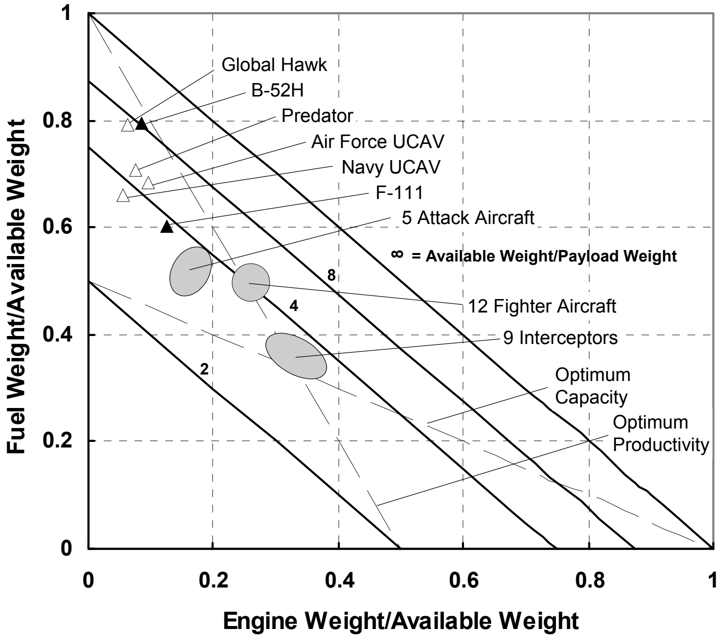
[2] Payload is defined here as expendable payload plus mission equipment

Table 5. Weight Distributions of Some UAVs

	Global Hawk	Predator B	AF UCAV[a]	Navy UCAV	Fire Scout
Takeoff Gross Weight	25,600	6,400+	15,000	26,000	2,550
Empty Weight	9,200	2,700	8,000	12,000	1,450
Internal Fuel	14,400	3,000	5,500	10,000	900
Payload	2,000	700	1,500	4,000	200
Engine	AE3007H	FJ44/TPE331	F124	F124/PW308	250-C20W
Engine Weight	1,600	550/385	1,300	1,300/1,400	170
Thrust, SLS	7,580	2300/776 hp	6,300	6,300/8,350	258 hp (derated)

Sources: References [1 through 4].

[a] The evolving Air Force UCAV program now also includes a heavier version, powered by the F404-400D engine.



Source: Adapted from Reference [6]; UAV characteristics added.

Figure 2. Weight Distribution Characteristics of Some Military Aircraft

Figure 2 displays the relationship among fuel weight fraction (fuel weight/available weight), the engine weight fraction, and the inverse of the payload weight fraction. The location of a particular vehicle on Figure 2 provides an indication of the value placed upon range, speed or maneuverability, and payload for the mission of the aircraft. For example, vehicles located toward the upper left corner perform missions that place a high value on range (or endurance), and vehicles located toward the lower right corner place a high value on speed or maneuverability. Two reference lines in Figure 2 aid in the interpretation. Vehicles on the line marked "optimum capacity" have approximately maximum values of the range-payload product; such vehicles can be considered to be designed for optimum capacity (e.g., ton-miles). Similarly, vehicles on the line marked "optimum productivity" have approximately maximum values of the product of specific vehicle power (or thrust) and payload; such vehicles can be considered to be designed for optimum productivity (e.g., ton-miles/hour).

These reference lines serve to divide vehicles roughly into four different types, depending on the relative priorities assigned to range, specific vehicle power, and payload. For example, for vehicles located above the optimum-capacity line and to the left of the optimum-productivity line, range (or endurance) has been most highly valued, payload next, and vehicle specific power the least valued. Also shown in Figure 2 are weight distributions of actual vehicles as well as the developmental UAVs listed in Table 5. It is pointed out in Reference [6] that vehicle classes (e.g., attack aircraft) are in expected locations in Figure 2, and the weight distributions tend not to vary with time. For a more thorough discussion, see Reference [6].

There are two points to note in Figure 2 regarding UAVs. First, the C4ISR UAVs (Global Hawk and Predator B) place a high value on range and/or endurance and are similar to strategic bombers in weight distributions. This is an expected result, on the basis that the sensor payloads of these UAVs are relatively light and valuable—much like the nuclear weapons for which strategic bombers were designed—and the most desired characteristic is range and/or endurance. Second, the combat UAVs (Air Force and Navy UCAVs) place a greater value on range and/or endurance than attack aircraft. This may not be an expected result, since it is reasonable to suppose that combat UAVs would have similar missions to attack aircraft. As mentioned earlier, however, it seems likely that all UAVs—regardless of specific mission—will have a surveillance and reconnaissance role. Endurance will be valuable in combat UAVs for target location and identification purposes.

On the basis of the preceding considerations, weight distributions for four notional UAVs have been defined as shown in Figure 3, for the purpose of evaluating engine benefits. The C4ISR weight distribution is essentially the same as that of the Global Hawk; it is assumed that range/endurance will continue to be the most highly valued characteristic; hence, the fuel fraction will be high. UCAV1 has a weight distribution similar to the Air Force and Navy UCAVs, with range still highly valued, but emphasis on the payload fraction increased as compared to C4ISR aircraft. UCAV2 has a weight distribution similar to attack aircraft, with greater value attached to payload and somewhat less to vehicle specific power than traditional attack aircraft. UCAV3 has a weight distribution with a value of vehicle specific power consistent with historical attack aircraft, and payload less valued. The weight distributions of UCAV2 and UCAV3 may lie outside the spectrum of eventual UAVs, but they are useful for illustrating limits. These four notional UAVs are used to estimate vehicle sensitivity to engine characteristics.

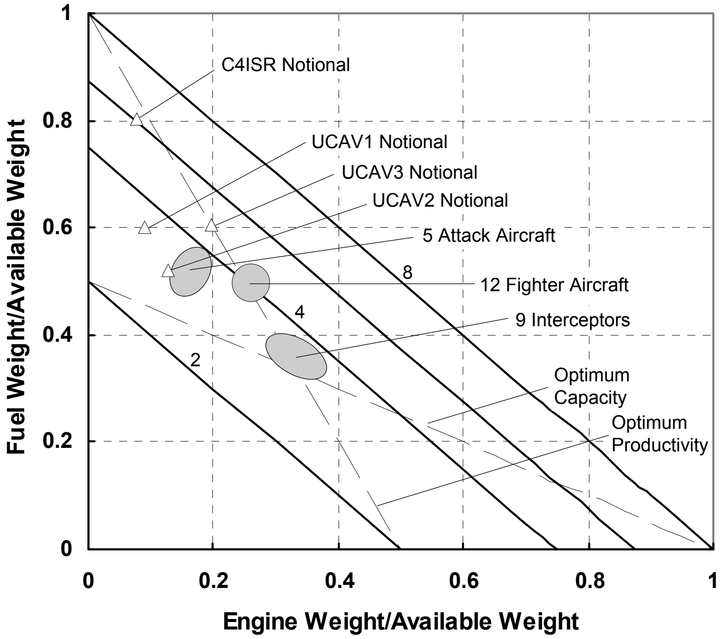


Figure 3. Weight Distributions of Notional UAVs

For completeness, the absolute weights assumed for these vehicles are shown in Table 7. For reference purposes, the engine thrust that corresponds to the engine weight is also shown for representative values of thrust/weight ratios of 5 and 6. Also shown are some cost characteristics that require explanation. The engine cost fraction is the ratio of engine procurement cost to the procurement cost of the basic air vehicle not including engines. Thus, an engine cost fraction of 0.2 represents an engine cost equal to 17 percent (0.2/(1+0.2)) of the cost of the air vehicle with engines. An engine cost fraction of 0.2, as for the C4ISR UAV and the UCAV2 is more or less typical. An engine cost fraction of 0.3, as assumed for UCAV1, represents an engine cost equal to 23 percent of the cost of the air vehicle with engines, an atypically expensive engine useful for illustrative purposes. The engine cost fraction of 0.3 assumed for UCAV3 may be considered typical for this relatively highly powered aircraft.

Table 7. Weight and Cost Characteristics of Notional UAVs

	C4ISR UAV	UCAV1	UCAV2	UCAV3
Takeoff Gross Weight (Fraction)	25,000 (1.0)	25,000 (1.0)	25,000 (1.0)	25,000 (1.0)
Vehicle Weight (Fraction)	7,500 (0.3)	10,000 (0.4)	10,000 (0.4)	10,000 (0.4)
Payload Weight (Fraction)	2,000 (0.08)	4,500 (0.18)	5,250 (0.21)	3,000 (0.12)
Fuel Weight (Fraction)	14,000 (0.56)	9,000 (0.36)	7,500 (0.3)	9,000 (0.36)
Engine Weight (Fraction)	1,500 (0.06)	1,500 (0.06)	2,250 (0.09)	3,000 (0.12)
Engine Cost Fraction	0.2	0.3	0.2	0.3
Payload/Vehicle Cost Ratio	1.0	0.0	0.0	0.0
Nominal Thrust (SLS, Th/Wt = 5/6)	7,500/9,000	7,500/9,000	11,250/13,500	15,000/18,000

The payload/vehicle cost ratio is merely the ratio of the payload cost to the cost of the air vehicle (including engines). A ratio of 1 is typical of a C4ISR aircraft wherein the payloads are quite expensive and not expended. The ratio of zero assumed for the UCAVs is an admitted underestimate, but the bulk of the payload is considered expendable (mission equipment constitutes the remainder of the payload) and, hence, is not fixed to the aircraft. The significance of the ratio is simply that for nonexpendable payloads, engine improvements can be used to reduce total fleet payload requirements and, hence, payload costs. For expendable payloads, engine improvements have no impact on total fleet payload requirements or payload costs.

Two additional points regarding these notional vehicles should be noted. First, there is no explicit consideration here of vehicle performance characteristics (range, speed, maneuverability) or mission profiles, simply because these characteristics are embedded in the weight distributions. The reasoning is, for example, if the "required" range/endurance for a C4ISR UAV results in a fuel weight fraction larger than assumed here, the requirement will be reduced to avoid the increased size and cost of the vehicle. In short, the additional range/endurance will be judged to be not worth the cost, in line with historical experience. Second, the takeoff gross weights do not influence the sensitivity of the vehicle to engine characteristics, at least to this order of approximation. The results of the analysis are applicable to UAVs over any reasonable range of aircraft gross weights (with the same weight distributions).

B. Benefits of Engine Improvements

Using the notional vehicles, the benefits of engine improvements can be assessed. Improvements in engine specific fuel consumption and output/weight ratio are equated to either greater aircraft payload capability or greater range/endurance. The measure of benefit selected here is the reduction of procurement costs for a fleet of "equal capability." Equal capability here is defined in two ways:

- *Equal fleet payload capability.* Engine improvements are used for greater unit payload capacity, while maintaining the same unit TOGW and unit procurement cost (except as the latter is reduced by engine procurement cost reduction). Maintaining the same total payload for the fleet results in fewer aircraft and, hence, reduced fleet cost. This definition is more appropriate to UCAVs with expendable payloads, where payload delivery capacity is the prime measure of capability, than to C4ISR UAVs.
- *Equal fleet endurance capability.* Engine improvements are used for greater fuel fraction and, therefore, greater unit endurance, while maintaining the same unit TOGW and unit procurement cost (again, except as the latter is reduced by engine procurement cost reduction). Maintaining the same fleet endurance then results in fewer aircraft and less total payload capacity and, hence, reduced fleet cost. This definition is more appropriate to C4ISR UAVs, where time-on-station capacity is the prime measure of capability, than to UCAVs.

Clearly the benefits of engine performance improvement can be taken differently; the measures here provide a representative assessment of the value. On the other hand, the impact of engine procurement cost is determined solely by its fractional cost contribution to the aircraft. That is, if the baseline engine cost fraction is 0.2, and the engine cost is reduced by 50 percent, then the relative cost of the air vehicle (including engines) will be reduced from 1.2 to 1.1, or by 8.3 percent.

Figure 4 shows the results for the C4ISR aircraft, in terms of the impact of percentage improvements in engine thrust specific fuel consumption (TSFC), weight/thrust ratio,[3] and procurement cost on total fleet procurement cost.[4] The "constant payload" lines correspond to equal fleet payload capability as described above, and the "constant endurance" lines correspond to equal fleet endurance capability. The major conclusions that can be extracted from Figure 4 are:

- TSFC is by far the most influential engine characteristic; thrust/weight ratio is the second most influential, and engine procurement cost has the least influence. This should not be surprising, given the priority assigned to endurance for a C4ISR UAV.
- These sensitivities to engine characteristics are similar to those for manned aircraft performing the same type of missions. From the standpoint of technology development, this implies that technology goals suitable for engines for manned aircraft of the C4ISR type are also suitable for C4ISR UAVs.

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[3] Thrust/weight ratio is, of course, the standard parameter; the weight/thrust ratio is, however, more indicative of the effect on an aircraft since weight is the price the aircraft pays. Improvements in weight/thrust ratio cannot be portrayed as dramatically as those in thrust/weight ratio (e.g., 100 percent improvement in thrust/weight ratio equates to 50 percent improvement in weight/thrust ratio).

[4] The Breguet range equation is used as the relationship between fuel fraction, TSFC, and range/endurance. For the constant fleet payload case, a reduced unit fuel weight fraction (a result of TSFC reduction) is replaced by an equivalent increase in unit payload weight fraction; for the constant fleet endurance case, the unit endurance increase is obtained from the Breguet factor (~TSFC × endurance) corresponding to the unit fuel weight fraction. This approximation assumes that fuel weight, payload weight, and engine weight are interchangeable within a given air vehicle; this, of course, is not quite true since fixed weight will generally require more air vehicle structure than fuel weight.

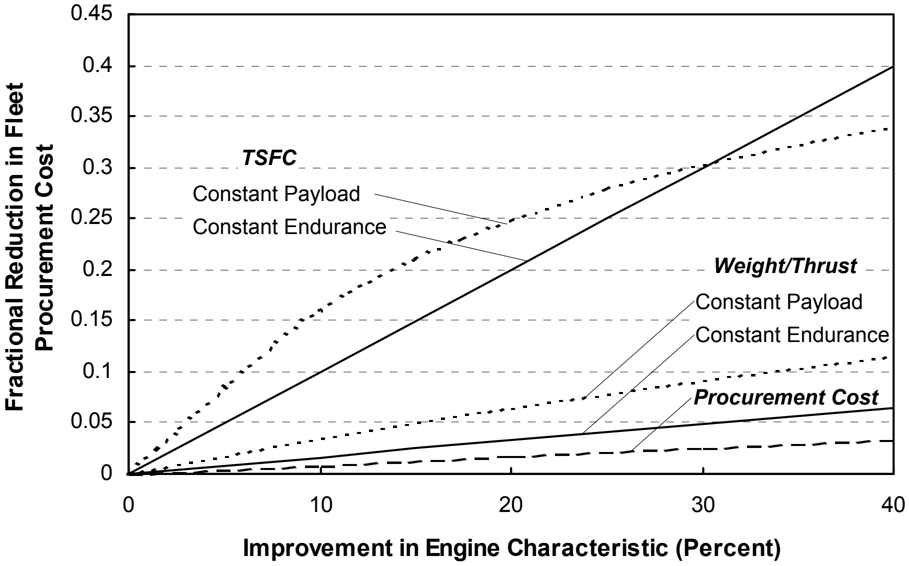

Figure 4. Engine Characteristic Sensitivities—C4ISR UAVs

The low impact of engine procurement cost is worth noting inasmuch as there is considerable emphasis by both aircraft and engine manufacturers on reduced engine procurement cost for UAVs. Engine procurement cost is, of course, a powerful discriminant if other things are equal; it is perhaps the difference between winning and losing a contract. The results here emphasize the importance of "other things," in particular the importance of TSFC; a lower-cost engine with a higher TSFC is unlikely to be a winner.

The typical order of magnitude of the potential benefits is also worth noting. For a fleet of 100 such aircraft with a unit procurement cost of $40 million—a representative figure—the baseline total fleet procurement cost is $4 billion. Per the assumptions made for the notional vehicle, $2 billion of this $4 billion is for the sensor payloads, and the remaining $2 billion is for the air vehicle including engines; the engines alone are $333 million. A 20 percent reduction in fleet procurement cost, as might be obtained from a 15 to 20 percent improvement in TSFC, for example, equates to $800 million. This is a significant amount, and it is clearly influenced by both the size of the fleet and the size of the aircraft—larger fleets and larger aircraft result in proportionally greater payoffs.

It should be pointed out that a reduction in fleet procurement cost generally understates the benefit, since there can be similar reductions in fleet maintenance cost. This applies to the "equal fleet payload" case, since the reduced number of aircraft implies reduced maintenance cost in like amounts; that is, if a 20 percent reduction in fleet procurement cost is achieved, then a 20 percent reduction in fleet maintenance cost is also achieved. On the other hand, maintenance cost reductions would be unlikely in the "equal fleet endurance" case: although the number of aircraft is reduced, the flying hours for each aircraft increase so as to maintain a constant total for the fleet.

Similar results are shown for UCAV1, UCAV2 and UCAV3 in Figure 5, for equal fleet payload capability, and similar conclusions can be made:

- TSFC is also the most influential characteristic for each of the notional UCAVs, followed by thrust/weight ratio and engine procurement cost.
- These sensitivities to engine characteristics are not quite the same as for manned combat aircraft: TSFC is likely to be more important in UCAVs than in attack aircraft, due to the previously mentioned desire for increased range/endurance; thrust/weight ratio is likely to be less important in UCAVs than in either fighters or attack aircraft, due to the lesser demand for maneuverability in UCAVs. Of the three notional UCAVs, only the relatively highly powered (and possibly non-representative) UCAV3 exhibits a moderately strong sensitivity to thrust/weight ratio, but the sensitivity to TSFC is significantly greater.
- From the standpoint of technology development, technology goals suitable for manned combat aircraft may need some reprioritization to achieve proper emphasis on TSFC reduction for UCAV applications. This is not to say that further improvements in thrust/weight ratio have negligible impact. The nature of turbine engine technology is such that foreseeable improvements in thrust/weight ratio are greater than foreseeable improvements in TSFC. Figure 6 indicates the influence of thrust/weight ratio for two reasonable levels (5 percent and 10 percent) of TSFC improvement. Since a 40 percent improvement in weight/thrust ratio may be considered reasonable, the essential point is that the benefits from future TSFC reductions and from future weight/thrust reductions may be of the same order of magnitude.

The typical order of magnitude for the potential benefits is somewhat different than for a C4ISR UAV. For a fleet of 100 UCAVs, with a unit procurement cost of \$20 million—again a representative figure—the total fleet procurement cost is \$2 billion, all for the air vehicle (the payload is considered expendable, and, hence, there are no fixed payload costs). Per the assumptions for UCAVs, the engines account for \$462 million for UCAV1 and UCAV3, and \$333 million for UCAV2. A 20 percent reduction in fleet procurement cost, as might be obtained from a 5 to 10 percent improvement in TSFC and a 20 to 30 percent improvement in weight/thrust ratio is \$400 million—still a significant amount but only-half that for the C4ISR example. Again, larger aircraft, greater fleet sizes, and consideration of the impact on fleet maintenance cost will magnify these benefits.

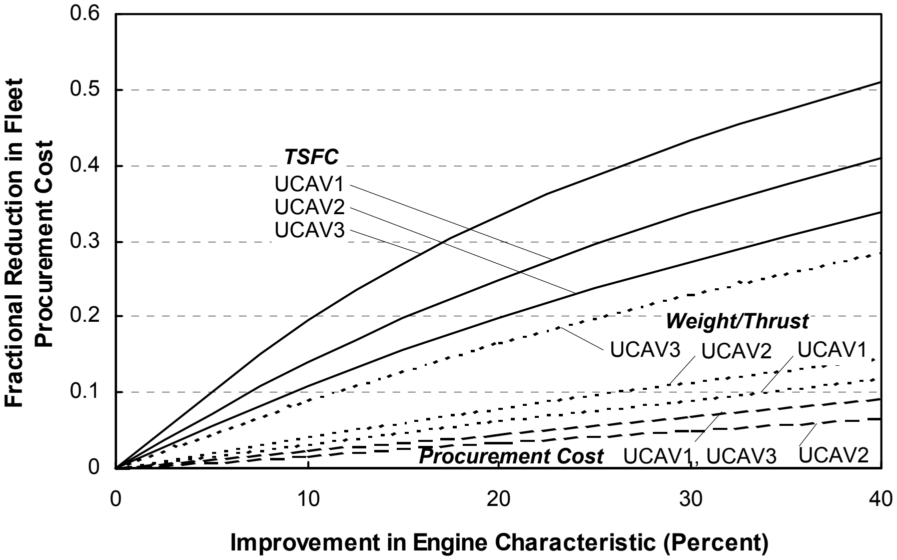

Figure 5. Engine Characteristic Sensitivities—UCAVs

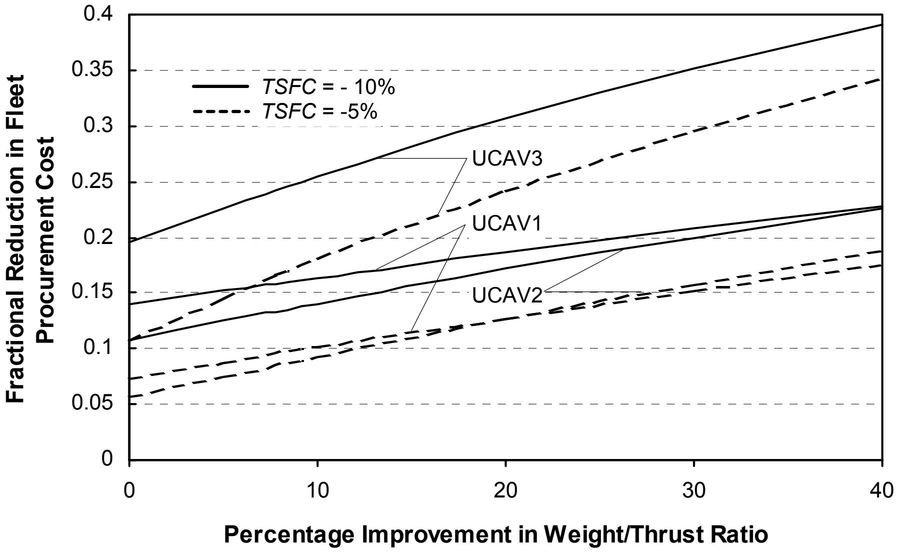

Figure 6. Influence of Weight/Thrust Ratio on Engine Benefits for Two Levels of TSFC Improvement—UCAVs

C. Impact of Engine Development Cost

It is well known that turbine-engine development costs are significant, particularly for the development of new engines, but development costs of derivative engines can also be appreciable. One issue concerning engines for UAVs is whether the benefits of a new, or derivative, engine offer a sufficient return on the development-cost investment. The magnitude of these benefits depend upon two factors: (1) the improvements in engine characteristics—TSFC, thrust/weight, procurement cost, and so on—offered by a new or derivative engine as compared to an existing engine and (2) the number of systems to be procured.

Inasmuch as engine development costs are difficult to estimate, the approach taken here is to measure the development cost by the number of engines whose cumulative procurement cost is equal to the development cost. Typically, this number is on the order of 500 for a new engine (e.g., an engine with an average unit procurement cost of $2 million over 500 engines costs about $1 billion to develop), but it can be lower for a new engine and substantially lower for a derivative engine. Using this measure, the ratio of fleet procurement cost savings (as defined in the previous section) to the engine development cost can be easily determined.[5]

Figures 7 and 8 show the results for the notional C4ISR UAV for the equal fleet endurance case. Figure 7 shows the ratio of fleet savings to engine development cost as a function of reduction in TSFC and the ratio of the number of vehicles in the fleet (N) to the number of engines with cumulative procurement cost equal to the engine development cost (N_e). A minimum return for investing in engine development would seem to be a fleet procurement savings of twice the development cost; Figure 7 indicates that anything less than that is considered to be inadequate payoff.[6] A more robust return would be savings of three or more times the development cost, indicated by the lightly shaded area in Figure 7. Benefits of this magnitude would seem to mandate the development of an engine. Recalling that TSFC is the most

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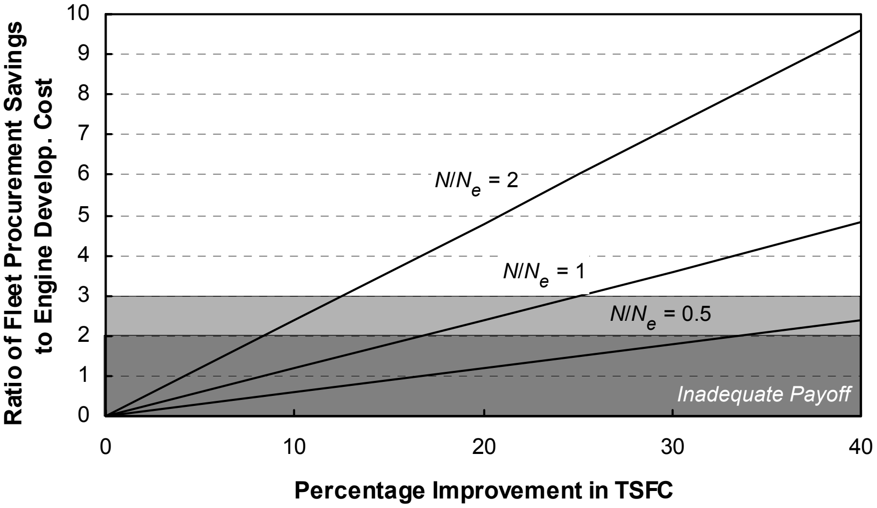
[5] If $\Delta\$$ is fleet procurement cost savings, N is the number of vehicles in the fleet, $\$_s$ is the aircraft system unit cost, $\$_e$ is the engine unit cost, $\$_{ed}$ is the engine development cost, and N_e is the number of engines with a cumulative procurement cost equal to the development cost, then $\Delta\$/\$_{ed} = (\Delta\$/N\$_s) \times (N/N_e) \times (\$_s/\$_e)$, where the first term on the right-hand side is the fractional reduction in fleet procurement cost displayed previously.

[6] The annualized return on investment depends upon the duration of the development and the procurement. To oversimplify, if it is assumed that the development cost is a lump sum, and the fleet savings will be achieved uniformly over 15 years following this investment, then a ratio of fleet procurement savings to engine development cost of 2 is equivalent to an annualized return of 7.6 percent, and a ratio of 3 is equivalent to an annualized return of 9.7 percent.

influential engine characteristic, and that TSFC improvements of 10 percent over existing engines are likely to be substantial, it seems clear that a relatively large system buy would be required to justify the development of a new engine for a C4ISR UAV—on the order of $N/N_e = 2$. If, for example, N_e is 500, then the number of systems required to justify engine development is on the order of 1,000. That is a large system buy.



Notes: N = number of vehicles in fleet
N_e = number of engines with cumulative procurement cost equal to development cost

Figure 7. Potential Benefits of TSFC Reduction Compared to Engine Development Cost—C4ISR UAV

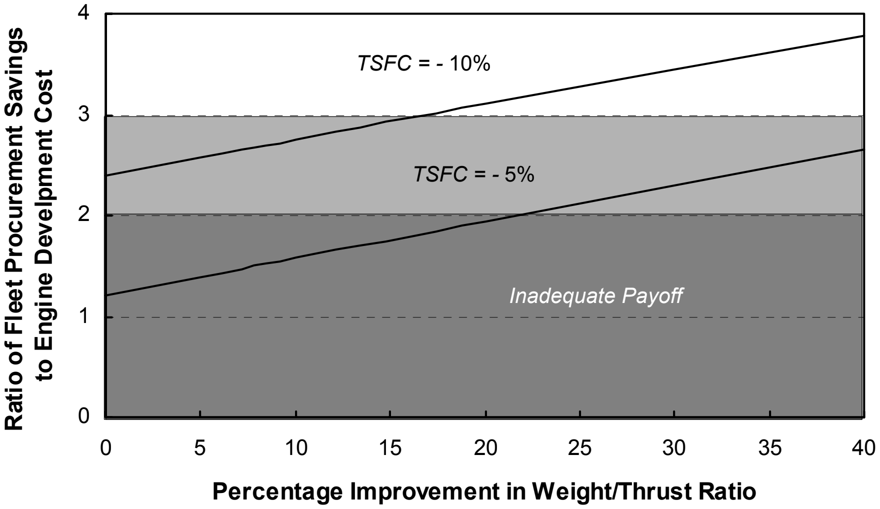


Figure 8. Potential Benefits of TSFC and Weight/Thrust Reductions Compared to Engine Development Cost—C4ISR UAV

Figure 8 shows the effect of including potential weight/thrust ratio reductions as well as specific fuel consumption reductions. Here the results are for a ratio of N/N_e = 2 (the ratio of procurement cost savings to engine development costs is linearly proportional to N/N_e). The two values of TSFC reduction shown—5 percent and 10 percent—are in the range of reasonable expectations for a new engine as compared to an existing engine. It seems apparent that not only would a relatively large buy be required to justify the development of a new engine, but a substantial improvement in TSFC (as compared to an existing engine) would also be required—increases in thrust/weight ratio are not likely to be adequate. For example, for a TSFC reduction of 10 percent and a thrust/weight increase of 100 percent (a weight/thrust reduction of 50 percent), the fleet procurement cost savings/engine development cost ratio is slightly greater than 4 for N/N_e =2; to achieve a ratio of 3, N/N_e would be slightly less than 1.5, still a large system buy.

The development of derivative engines may be easier to justify, depending upon the situation. For example, the development cost of replacing the fan of an existing engine may be only 10 percent of the development cost of a new engine, resulting in an N_e of perhaps 50. It can be inferred from Figure 8 that a system buy of 100 (N/N_e = 2) and a TSFC improvement of about 7 to 8 percent would justify development.

Similar results for the notional UCAVs are shown in Figure 9 for TSFC reductions and Figure 10 for weight/thrust reductions, for N/N_e = 2. It is worth pointing out that although reductions in TSFC produced greater fleet savings for UCAV1 than for UCAV2 (see Figure 5), the situation is reversed in the ratio of savings to engine development costs. This is due to the assumption of a higher engine procurement cost for UCAV1, and hence a higher development cost for the same N_e. For comparison purposes, the results for UCAV1 with the engine procurement cost of UCAV2 are shown as “UCAV1R.” The basic conclusion, however, is the same as for the C4ISR UAV, but with more emphasis: a substantial improvement in TSFC, and quite a large buy would be required to justify the development of a new engine.

This point is made graphically in Figure 11, which indicates the size of the buy needed to achieve a ratio of fleet procurement cost savings to engine development cost of three. On the basis that an improvement in weight/thrust ratio of 40 percent may be reasonable, then an N/N_e value of about 1.5 would be sufficient for a TSFC reduction of 20 percent, and an N/N_e value of about 2 would be sufficient for a TSFC reduction of 10 percent. The corollary to this observation is that if system buys reach that magnitude, the benefits of a new engine are substantial. The previous comments regarding derivative engines apply here also.

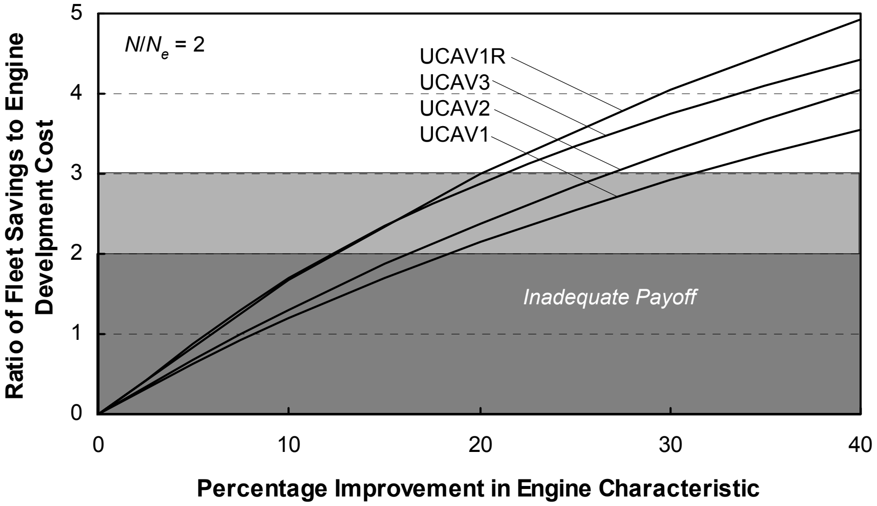


Figure 9. Potential Benefits of TSFC Reduction Compared to Engine Development Cost—UCAVs

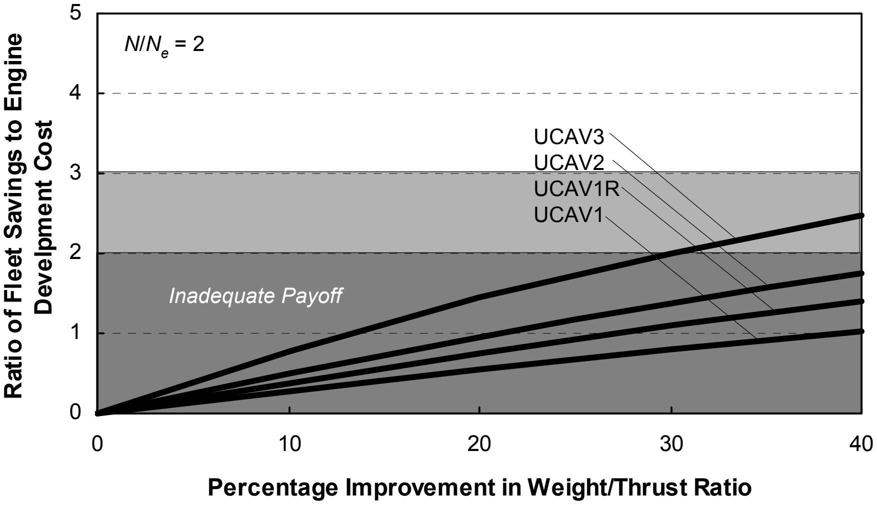


Figure 10. Potential Benefits of Weight/Thrust Reduction Compared to Engine Development Cost—UCAVs

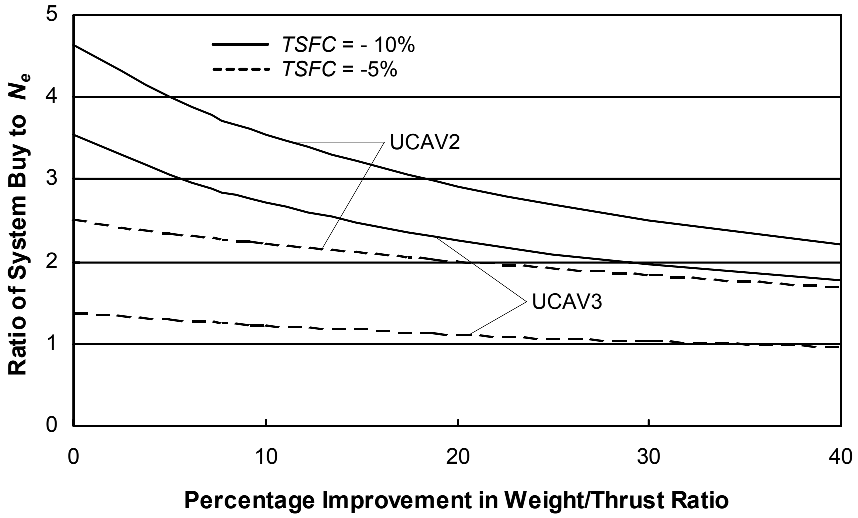


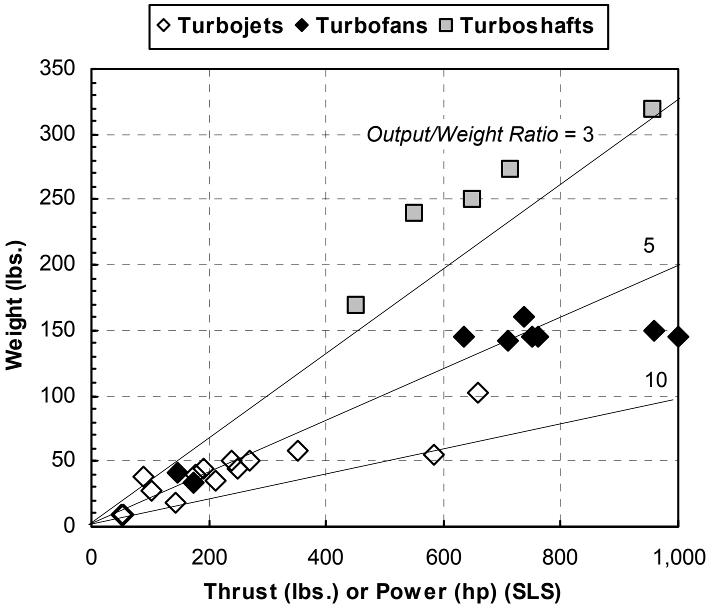
Figure 11. System Buy Required to Achieve Fleet Procurement Cost Savings of Three Times Engine Development Cost

IV. Use of Existing Engines for UAVs

In considering engine development for UAVs, a key factor is obviously the improvement in specific fuel consumption that can be made with a new engine versus a derivative or existing engine. Thrust/weight ratio improvement will also contribute, of course, but it is unlikely to offer sufficient benefit alone to merit the development of a new engine. The magnitudes of possible improvements are largely determined by the characteristics of existing engines.

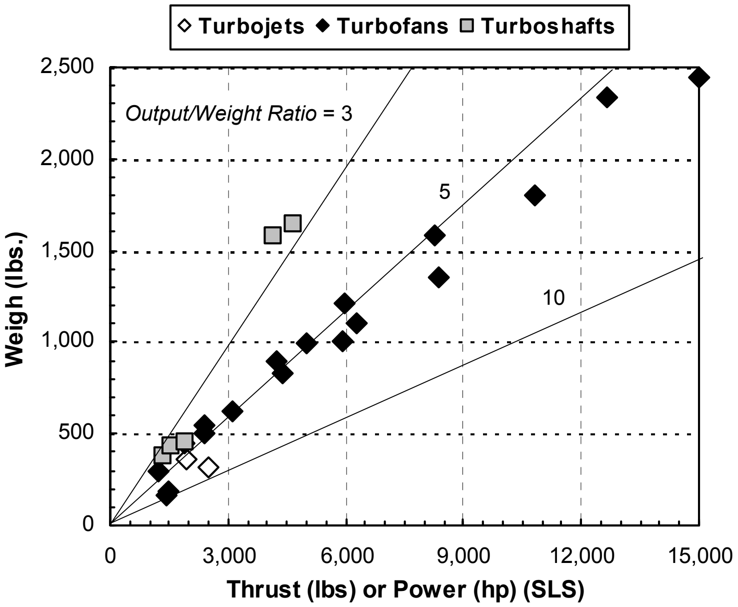
A. Existing Engines with Potential Applicability

Figures 12 and 13 show the thrust and weight characteristics of turbine engines in the range of 0 to 15,000 pounds of thrust or horsepower. All of these engines have potential applicability to UAVs, and it is clear that, from the standpoint of thrust or power level, the spectrum of UAV needs is adequately covered. But as the preceding discussion indicates, it is the performance characteristics—most importantly, the specific fuel consumption—that largely determine the applicability.



Source: Data from References [2, 3, 7, 8, and 9].

Figure 12. Existing Engines Potentially Applicable to UAVs (Less Than 1,000 Pounds of Thrust or Horsepower)



Source: Data from References [2, 3, 7, 8, and 9].

Figure 13. Existing Engines with Potential Applicability to UAVs (1,000 to 15,000 Pounds of Thrust or Horsepower)

It is difficult to collect data on specific fuel consumption of existing engines at relevant flight conditions. Some of the data is considered proprietary, and much of the data available are not at the same flight condition, which makes comparison difficult. The approach taken here is not to attempt a compilation of such data. Rather, the physical laws and estimates of component efficiency levels are used to determine the general characteristics of existing engines and the limits on future performance. An existing computer program [10] was used to estimate specific fuel consumption as a function of cycle parameters. For the purposes here, it is assumed that the design point of all engines is for the flight condition M = 0.8, 40,000 feet. The component efficiency levels assumed are representative of large turbofan engines. Calculations have been made for overall pressure ratios of 16 to 100, and turbine inlet temperatures from 2500^0 F to 3500^0 F. The results, shown in Figure 14, require some explanation.

As evident in Figure 14, the specific fuel consumption is essentially a function only of cycle pressure ratio and specific thrust. Specific thrust is an important parameter, both thermodynamically and practically; as specific thrust decreases, the propulsive efficiency increases and the amount of airflow through the engine, and hence its size, increases. For a given overall pressure ratio and specific thrust, turbine inlet temperature has but a slight effect on TSFC—perhaps one or two percent at the most. Turbine inlet temperature determines the highest specific thrust level that can be reached, but its major impact is to reduce the size of the "core"—the unit consisting of the high-pressure compressor, the combustor, and the high-pressure turbine. As turbine inlet temperature increases, a given value of specific thrust is produced by an engine with a higher bypass ratio, a smaller core, and therefore a higher thrust/weight ratio. Since the flight condition is assumed to be the design point and high component efficiency levels representative of large turbofan engines are used in these calculations, the results can be viewed as the limits of performance of turbine engines of given overall pressure ratio and specific thrust.

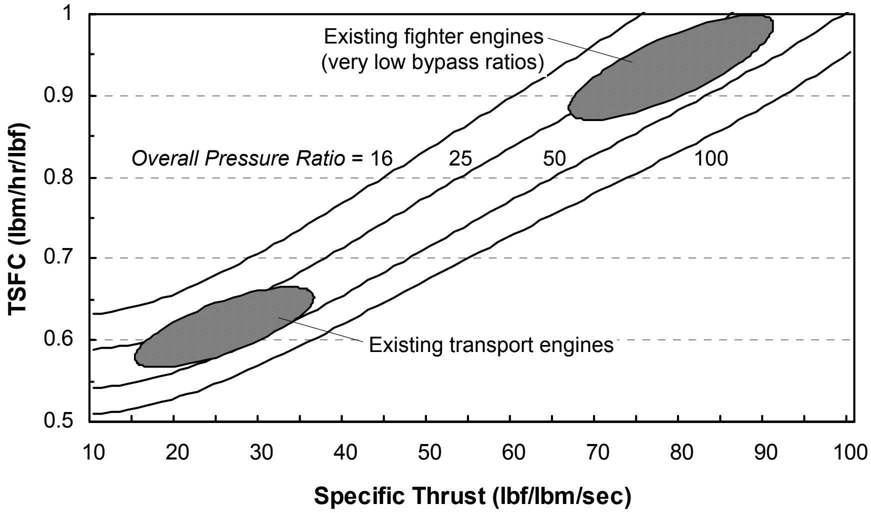


Figure 14. Representative Specific Fuel Consumption Limits, Turbofan/Jet Engines (M = 0.8, 40,000 feet)

It would be exceedingly difficult to achieve a TSFC below that indicated in Figure 14. It should be noted that there is a difference between small and large engines; small engines will operate at lower overall pressure ratios than large engines, and their component efficiencies will be lower. Accordingly, TSFC will be higher in small engines than large ones, and will generally be higher than indicated by the curves in Figure 14.

Also shown in Figure 14 are areas that encompass most of the larger existing engines. The high-specific-thrust engines are generally the low-bypass-ratio fighter engines, where low engine frontal area and high thrust/weight ratio are very important. The low-specific-thrust engines are high-bypass-ratio engines for both large and small transport aircraft, where low specific fuel consumption is much more important than either thrust/weight ratio or frontal area. There is a noticeable lack of existing engines in the intermediate specific thrust range, presumably due to lack of applications.

B. Adaptability of Existing Engines for UAV Applications

As used here, the term "adaptability" means that an existing engine can be made suitable for an application with only minor modifications that do not involve replacing any major engine component. Based on the sensitivities indicated in Chapter 3, Section B, an absolute requirement for adaptability is an engine specific fuel consumption that is reasonably representative of the state of the art at a specific thrust (and engine frontal area) acceptable for the aircraft. There are, of course, other considerations for adaptability, and these will be discussed in Chapter 5.

The two classes of UAVs considered here—C4ISR and combat—have different requirements for acceptability. Figure 15 shows the likely areas of interest for the two types of applications, and requires some explanation.

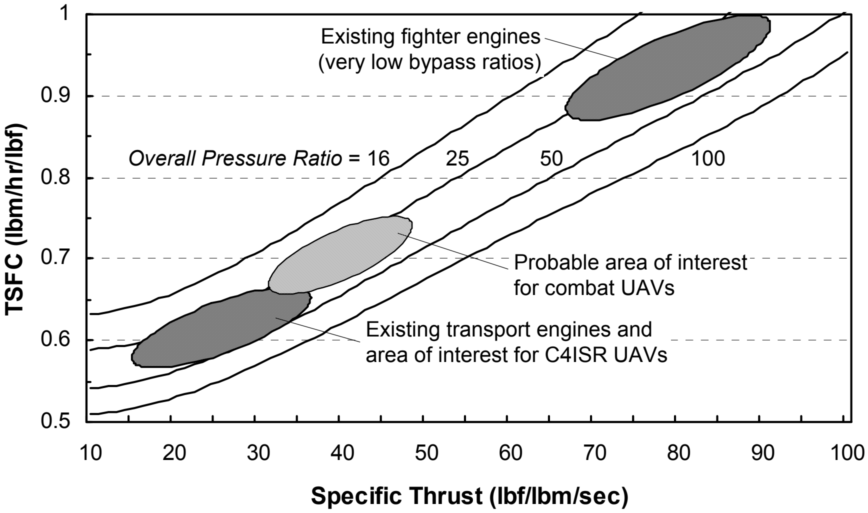


Figure 15. Probable Areas of Interest for Specific Fuel Consumption of UAV Engines

C4ISR applications have thus far been driven by the desire for maximum endurance, with little emphasis on signature reduction. Thus engine frontal area has not been unduly limited, and the low specific thrust necessary for low specific fuel consumption has been tolerated. It seems likely that this will continue to be the case, at least for the high-altitude UAVs. Accordingly, the preferred engines will be high-bypass-ratio, low-specific-thrust turbofans; these are also the characteristics of both small and large transport aircraft engines. If the thrust levels of existing (or new) transport engines are adequate for C4ISR UAVs, these engines can be adapted for UAV applications—as, in fact, the AE3007H has been adapted for Global Hawk. Using an adaptation may result in some small penalties in specific fuel consumption and perhaps procurement cost when compared to a new engine development, but given the apparently limited potential market for a single model aircraft it is unlikely that a new engine development can be justified.

Combat UAVs, although still in their formative stages, have placed some emphasis on signature reduction as well as increased endurance and/or range. The optimum tradeoff between these two conflicting characteristics remains to be determined, but it seems certain that the high-bypass-ratio, low-specific-thrust engines will not be suitable due to the large airflow and frontal area required. On the other hand, the very low-bypass-ratio, high-specific-thrust engines will not be suitable either, due to their high specific fuel consumption, which would lead to reduced endurance or larger, more expensive aircraft. Figure 15 indicates the probable area of optimum tradeoffs between specific thrust and specific fuel consumption for combat UCAV engines. As noted previously, there do not appear to be any existing engines with these characteristics; hence, a significant modification of an existing engine, or perhaps a new engine, will likely be required. In the context of the previous discussion on the impact of TSFC, a reduction of about 20 percent from existing low-bypass-ratio, high-specific-thrust engines is desired.

V. Special Considerations for UAV Engines

The first-order characteristics of engines—thrust, weight, specific fuel consumption, and cost—are obviously major considerations in UAV applications. There are, however, other factors worthy of consideration. These factors are broadly of two types: (1) technical matters, concerning engine design features or operating characteristics that may be important in UAV applications, and (2) management matters, concerning engine development and qualification. They are discussed separately here.

A. Technical Considerations

Four areas that may require special treatment in UAV engines are: (1) power extraction; (2) high-altitude effects; (3) potential long-term storage requirements; and (4) performance-life-cost tradeoffs. These are discussed in turn.

1. Power Extraction

Air vehicle and payload requirements for power and cooling can conceivably vary over a wide range for UAVs—from the more conventional requirements akin to combat aircraft, to the need for relatively significant power and cooling at high altitudes, to the prospect of extremely large requirements for directed energy weapons. Provision for these power requirements are likely to be more of an issue for UAVs because their propulsive power requirements are relatively modest. To illustrate, Figure 16 shows propulsive power output (i.e., thrust times velocity) as a function of thrust output in the stratosphere. For an aircraft with a 25,000-pound maximum takeoff weight, the maximum thrust required at altitude is likely to be in the range of 1,000 to 2,000 pounds, depending upon the vehicle and the altitude. The corresponding propulsive power output will be in the range of perhaps 1 to 2 megawatts (1,340 to 2,680 horsepower).

Power requirements for future C4ISR UAVs and UCAVs are somewhat speculative; the need for as much as 150 kw has been suggested. At this level, the power requirement is in the range of 7 to 15 percent of that required for propulsion (for a high bypass ratio turbofan operating at high altitude, 15 percent of propulsive power is also equivalent to about 10 percent of the power produced by the high-pressure turbine). The thrust capability of a given engine to provide both propulsion and power will depend upon how this power is extracted. If the power is extracted solely from the high-pressure spool (a customary practice because the starter must be connected to this spool), the thrust capability will be lower than if power is extracted from the low-pressure spool. This is because extracting a given fraction of power from the high-pressure turbine has a greater impact on engine operating conditions than does extracting the same fraction from the low-pressure turbine. That is, extraction from the high-pressure turbine results in lower rotational speeds, lower flow rates, and lower overall pressure rations than equivalent extraction from the low-pressure turbine. The magnitude of thrust difference depends upon details of the engine cycle—fan pressure ratio, bypass ratio, core pressure ratio, etc.—but a difference of 10 to 15 percent in thrust would not be unusual. This, of course, is a penalty that would be incurred for a UAV engine that was not modified for some power extraction from the low-pressure spool.

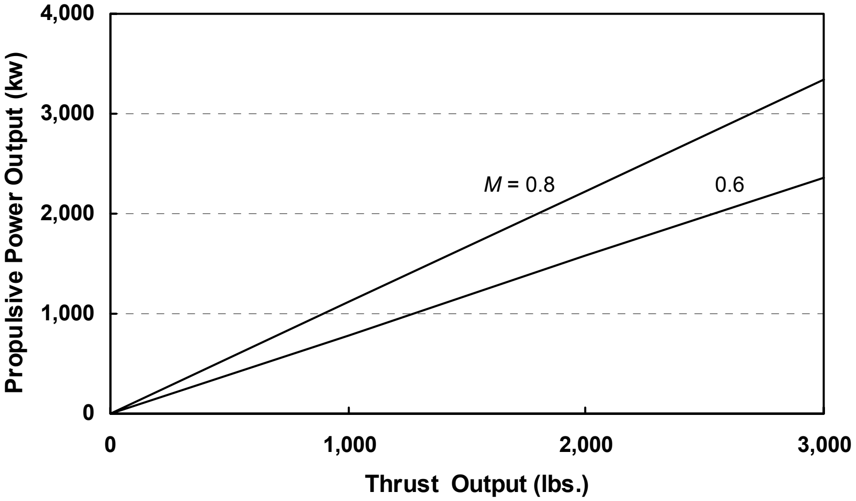


Figure 16. Propulsive Power Output in the Stratosphere

Some consideration is being given to the possible use of directed-energy weapons (DEW), primarily high-power microwaves or lasers, with UCAVs. Power requirements here may be in the range of 500 kilowatts to a few megawatts—about the power required for propulsion at cruise conditions. It seems unlikely that power extraction from a propulsion engine is a suitable solution in this case. It would result in an engine operating at low power conditions when the DEW power was not required, with an appreciable penalty in specific fuel consumption. It would also mean using a specialized engine and a specialized air vehicle for a small number of systems. A more optimal solution appears to be a separate power source for DEW, which can be considered part of the payload and permits an air vehicle suitable for applications other than DEW.

2. High-Altitude Effects

Operation at high altitudes (>60,000 feet, say) introduces several effects that must be considered in engine design and performance prediction. These effects include:

- *Low Reynolds numbers.* At the lower Reynolds numbers associated with higher altitudes (e.g., a Reynolds number at 65,000 feet is about 30 percent of that at 40,000 feet), boundary layers are thicker and losses are higher. This is a fundamental and well-known physical fact.
- *High fuel-turndown ratios.* Combustors must operate over a greater range of fuel flows in engines operating at high altitudes. This gives rise to potential difficulties with combustor stability, fuel atomization, and fuel coking at low fuel-flow rates. The ratio of maximum fuel-flow rate to minimum fuel-flow rate is the turndown ratio.
- *Case cooling and clearance control.* Heat transfer to the ambient atmosphere reduces at higher altitudes, resulting in less cooling of the engine case. This tends to cause overheating of the case and, more importantly, increases the clearances between the turbine and the turbine case, resulting in a loss in efficiency.
- *Low pressure-differences.* Lubrication systems, pneumatic valves, and internal engine thrust balance can depend upon absolute pressure differences. At high altitudes these pressure differences become smaller, and can result in inadequate operation.

None of these effects are unique to UAV applications, and several gas-turbine engines have been operated successfully at high-altitude conditions. Suitable attention to these effects in the design of new engines or modest modifications of existing engines should avoid potential difficulties.

3. Potential Long-Term Storage Requirements

As mentioned earlier, consideration is being given to placing some UCAVs in storage until needed in combat. Should this become a reality, then attention must be devoted to ensuring engines can function after long-term storage—5 years, say. Primary concerns for long-term storage include corrosion of various sorts, elastomeric material degradation, and permanent deformations due to gravity. All of the problems associated with long-term storage have previously been successfully addressed in cruise-missile engines, and should not cause undue difficulty in UAV engines. There is also at least one example of a commercial turbofan operating with minimum difficulties after being in storage for 10 years.

4. Performance-Life-Cost Tradeoffs

The possibility that the desired life of some UAVs may be considerably shorter than that associated with manned applications permits tradeoffs of life with either or both performance and cost. A convenient rule of thumb is that a 50^0 F change in turbine inlet temperature is equivalent to a factor of two change in life—increases in temperature decrease life, and decreases in temperature increase life. For example, given the same technology level, an engine for a UAV application with a desired life of 2,000 hours could operate at approximately 100^0 F higher turbine inlet temperature than an engine for a manned application with a life of 8,000 hours.

As discussed previously (Chapter 4, Section B), the effect of increased turbine inlet temperature for a new engine of a given pressure ratio is essentially a reduction in the size of the core needed to produce a given thrust at a given value of specific thrust. The effect on TSFC is relatively small. The major benefit is accordingly an increase in thrust/weight ratio, and perhaps a slight reduction in procurement cost. Alternatively, a higher turbine inlet temperature enables a new engine to be optimized at a higher pressure ratio, and achieve a somewhat lower TSFC.

For a derivative engine based on an existing core, the effect depends on the modifications of the low-pressure spool. If there are no modifications, then both the thrust and specific thrust levels will increase, resulting in a higher thrust/weight ratio and a higher TSFC. If the low-pressure spool is modified to increase the bypass ratio, then the thrust level can be increased without changing the specific thrust, resulting in a higher thrust/weight ratio and little change in TSFC.

These tradeoffs are, of course, well known, and apply equally well to engines for manned applications. Their primary benefit to UAV applications is that a core for a manned-aircraft engine can offer somewhat more performance capability at a reduced life, if the latter is acceptable.

5. Summary

The technical considerations just discussed are, of course, not unique to UAV engines. All of the areas have been addressed, at least to some degree, in previous engines. Perhaps it can be argued that consideration of all of these areas in a single engine, as might be required in some UAV applications, is unique. On the other hand, the areas are not in basic conflict, the technical details are well known, and accommodation should be straightforward. None of these factors are likely to provide sufficient cause for the development of a new engine or, with the possible exception of power extraction, a significantly modified engine.

B. Management Considerations

There are at least three features of the current status of UAVs that may pose some management issues in how engines are selected, developed, and qualified:

- *Unclear operational roles.* The operational roles of UAVs, particularly UCAVs, are emerging, but have not yet been completely defined. This introduces uncertainty in the specific engine requirements, the timing of development, and the numbers to be procured.
- *Reliance on derivative engines.* The potential reliance on derivatives of existing engines for operational systems, or stated somewhat differently, the potential lack of justification for the development of all-new engines due to limited procurement quantities and high development cost, poses a problem. Having to use a derivative engine reduces flexibility in both the engines ultimately available and, in turn, the associated air vehicles.
- *Uncertainty in qualification procedures.* The fact that the vehicles are unmanned suggests that qualification procedures may need to be adjusted accordingly, with a view toward reducing development costs.

The possible effect of these features on the management of engine development and qualification are examined in the following subsections.

1. Engine Development

Because the situation regarding development is somewhat different for C4ISR and UCAV applications, they are discussed separately here.

a. C4ISR Applications

The operational role of C4ISR UAVs is reasonably well established, and one such system, Global Hawk, is already in development. As discussed previously, the development of a new engine, or perhaps even a significantly modified one, for C4ISR applications is highly unlikely. The numbers to be procured are relatively small, and the engine characteristics desired are similar to those of commercial aircraft engines—as evidenced by the AE3007H in the Global Hawk. For future applications, it is obviously important to match the characteristics of the air vehicle to the availability of existing engines; an air vehicle that requires a new engine or engines is not likely to be developed. In matching vehicles to engines, it will be important to consider opportunities for, and limitations to, potential growth of the air vehicle. Historically, operational air vehicles have grown heavier with time, and engine thrust levels have been increased accordingly. Given the importance of specific fuel consumption in C4ISR applications, any growth in engine thrust must be accompanied by a proportional increase in airflow (to maintain constant specific thrust); the ability to achieve such airflow increases will need to be assessed.

Existing engines may require modifications for high-altitude operation and for significant power extraction. Modifications for high-altitude operation can be expected to be relatively minor, and should be able to be accommodated in a modest development program. These modifications have already been performed for the AE3007H in the Global Hawk, and would not be substantially different for other future candidate engines.

Modifications for significant power extraction, however, could be extensive, and arriving at a cost-effective solution will require tradeoffs between engine performance and development cost and air vehicle performance and cost. For example, the optimum *engine* solution is likely to be power extraction divided between the high-pressure spool and the low-pressure spool. This divided extraction will result in the greatest thrust output for a given engine and level of power extraction. It may also result in an extensive modification of the low-pressure spool and a relatively expensive development program. Depending on the cost of development, the overall result may not be the optimum *system* solution. Another possible solution is to extract all of the power required from the high-pressure spool, and accept the penalty to the air vehicle—which could be in terms of a larger engine, or lesser performance of the air vehicle. This solution would minimize the development cost associated with engine modification, and could possibly be the optimum system solution. The essential point is that these tradeoffs will need to be carefully examined in order to arrive at proper specifications for an engine.

b. UCAV Applications

In contrast to C4ISR UAVs, UCAVs will need at least one engine that is more than a minor modification of an existing engine to obtain a desirable tradeoff between specific fuel consumption and specific thrust. By virtue of the exploratory nature of UCAV development to date, all of the experimental models are incorporating, or plan to incorporate, engines that are not suitable for the ultimate system (e.g., the F124 in the small Air Force UCAV, the F404-400D in the large Air Force UCAV, and the F124 and PW308 in the Navy UCAV versions). To progress from this state to engines suitable for ultimate application involves at least four related questions:

- *Is it possible for a common engine, or modest variants of a common engine, to satisfy the requirements for both Air Force and Navy UCAVs?* The current embryonic nature of UCAVs, and the similarity in size and thrust requirements of Air Force and Navy versions, suggests that there may be an opportunity to make minor adjustments to perceived mission requirements that would make a common engine possible. It may turn out, of course, that a common engine or an "almost" common engine is not practical; but that conclusion is best made only after a thorough investigation of the possibilities. Clearly a wider application of a given engine is beneficial for DoD, since it may permit development of an engine that provides greater UCAV capability, reduced UCAV cost, or both.
- *What is the appropriate magnitude of engine development?* There are four broad possibilities: (1) developing a new fan for an existing core and low-pressure turbine, (2) developing a new low-pressure spool, (3) developing a new low-pressure spool and modifying the core, and (4) developing an all-new engine. The choice here involves the following factors: what the manufacturers can offer; the cost of the development; the impact on the cost-effectiveness of the system(s); and the number of engines likely to be procured. A solicitation for engine development will have to include consideration of these factors to specify an appropriate range of acceptable engine performance and the evaluation criteria for proposals.
- *Shall the engine be contracted for as government-furnished equipment (GFE)*[7] *or contractor-furnished equipment (CFE)?* If a common or "almost" common engine is practical, then engine development would no doubt be contracted for as GFE; it seems awkward at best and impossible at worst to treat engine development as a subcontract to one or more air vehicle manufacturers. If an engine is unique to one air vehicle, then

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[7] GFE implies a contract between the procuring government agency and the engine manufacturer for the development and production of engines; CFE implies a subcontract between the air vehicle manufacturer and the engine manufacturer for the development and production of engines.

treating it as CFE is practical, but may not be optimal. Common criticisms of CFE engine programs include lack of adequate government oversight and unwarranted pressure on the engine manufacturer to reduce costs to help offset unexpected costs in the air vehicle program. Common criticisms of GFE engine programs are government micromanagement and inadequate attention to development costs. There is general agreement, however, that some government oversight by engine professionals is necessary to ensure all engine issues are identified and addressed promptly. This need is present in derivative engine developments as well, since such matters as "common cores" or "slight" modifications of existing engines can involve significant design and development considerations.

- *What should be the timing and nature of engine development programs?* The historical practice of initiating a complete engine development program when the air vehicle program is fully defined (including air vehicle requirements and projected procurement quantities) may not be suitable, given the current state of perceived UCAV requirements. It may be necessary to initiate an engine development of some sort before a commitment to sizeable procurement quantities would be prudent. For example, it may be desirable to field a limited number of experimental UCAVs to evaluate them in an operational environment. This suggests the possibility of initiating a "limited" engine development, to bring an engine to the point of initial flight release and provide a limited number of such engines with no commitment to proceed further. In any event, a decision will be needed on the timing and initial extent of engine development.

The optimum answers to these questions are not obvious; arriving at a suitable course of action requires a thorough examination by the interested parties. Such an examination—a suitable undertaking for OUSD(AT&L)—should take place before any commitment is made to engine development for UCAVs.

2. Qualification Procedures

Since the cost of development is likely to be a significant consideration in UAV engines, some examination of necessary engine qualification procedures is appropriate. Certainly a common theme among engine manufacturers is that the qualification requirements might be reduced for UAV engines; their suggestions range from a judicious adaptation of commercial standards to the development of special qualification procedures.

The following three current engine specifications could be applied to various kinds of UAV engines: the commercial engine certification requirements of the Federal Aviation Administration (FAA) [11], the DoD specification for engines for manned aircraft [12], and the Air Force specification for expendable UAV engines [13]. Appendix A gives an overview comparison of the requirements of these specifications.

In terms of the number of specific requirements to be satisfied, the specifications are quite different for turbofan/turbojet engines: the FAA identifies 30 requirements; the manned aircraft engine specification identifies 200; and the expendable specification identifies 84. The actual differences are not quite so large, since the commercial engine specification is much more aggregated, and the Air Force specification somewhat more aggregated, than the DoD specification. A thorough examination of these three specifications is beyond the scope of this assessment, nor is such an assessment likely to be productive. At the risk of some oversimplification, the major differences are:

- *Durability and maintainability demonstrations.* The commercial engine specification requires much less demonstration of durability and maintainability than does the DoD specification. For example, the FAA requires a 150-hour durability test, while DoD has typically required a full lifetime test in addition to demonstrations of damage tolerance. This, of course, is not surprising; the primary interest of commercial certification is safety of flight and, hence, the overriding consideration is whether an engine will operate satisfactorily in between inspection intervals. The ultimate life of an engine or its maintenance burden is of lesser concern to the FAA (but not to the airlines and engine manufacturers). DoD, on the other hand, is not only concerned with safety of flight, but also desires an engine to perform for a specified life and to not create a large maintenance burden.
- *Long-term storage and mission reliability for expendable engines.* The expendable engine specification requires virtually no demonstration of low-cycle fatigue life or damage tolerance, but does require demonstration of long-term storage capability and mission reliability (the latter also equates to a demonstration of durability). Again, this is not surprising inasmuch as operational usage consists of long-term storage followed by one-time use.

All three specifications also have some flexibility. First, the quantitative requirements—such as desired life, operating envelope, reliability, and so on—are, of course, specific to a given engine and application. Second, there is also some flexibility in how the satisfaction of each requirement is to be verified; the specifications do permit some latitude with regard to the amount and nature of verification testing required. The essential points here are that these specifications have been carefully formulated for their intended purposes, and that they are adaptable to a wide spectrum of engines.

It is frequently pointed out that the qualification of a military fighter engine costs significantly more that the certification of a commercial engine, the implication being that the military qualification requirements are extreme and should be simplified. A rule of thumb put forward by some engine manufacturers is that it costs about twice as much to qualify a fighter engine than to certify a commercial transport engine. Given the long lifetimes desired and the severity of operating conditions for fighter engines, the cost difference necessary to demonstrate that all of these requirements have been met may not be so surprising. It is difficult to identify individual requirements in the military engine specification that could be eliminated. One might question the wisdom of, for example, specifying long lifetimes that need to be demonstrated in a qualification program; but specifying long lifetimes would not be a difficulty with the generic specification but rather with the quantitative requirement established by the individual program.

With regard to the types of UAV engines considered in this report, it is clear that specifications cannot be relaxed because the vehicles are inexpensive and expendable; as stated earlier, the vehicles are neither. The operational usage and lifetime desired may be significantly different for UAV engines as compared to engines for manned aircraft; the requirements for mission reliability and avoiding loss of aircraft and high maintenance burdens will, however, be similar to those for manned aircraft engines. These facts, coupled with the existence of carefully formulated and adaptable engine specifications, make it unlikely that developing a new generic specification for UAV engines would be a productive enterprise. It is difficult to visualize an outcome that would be significantly different from existing generic requirements.

The existing specifications do not dictate the cost of engine qualification. The costs of qualification of UAV engines may be reduced by attention to three areas:

- *Definition of the quantitative requirements.* Obviously, the requirements for operational usage, life, maintenance requirements, and the like should match the intended use. It appears that the nearer term UAVs will have a less-demanding operational envelope than, say, attack aircraft, will have lesser life requirements, and may have somewhat more tolerance for maintenance. Appropriate specification of these requirements will reduce the amount and nature of developmental testing required.
- *Consideration of continued, or spiral, development.* If the spiral development approach is being followed, it may be possible to reduce the initial life,

durability, and reliability requirements of an engine. Turbine engines have a long history of growth in these characteristics after initial entry into service, through minor design changes to correct service-revealed deficiencies. Indeed at some point it becomes more cost-effective to rely on operational use for identifying opportunities for engine improvement than to rely on continued developmental testing.

- *Verification by similarity for derivative engines.* If a UAV engine is a derivative of an existing engine—for example, by using a common core—then the verification of some requirements may be possible by similarity, with perhaps some additional analysis, as opposed to developmental testing.

All three of these areas are, of course, engine- and program-specific. It is not possible to find a universal solution for all engines and all programs, but careful attention and perhaps negotiation at the outset of a program should produce a cost-effective development.

VI. Unconventional Engine Candidates

Two types of engines have generated some interest for potential UAV applications: fuel cells and pulse-detonation engines. The potential of these engines for application to UAVs is assessed here.

A. Fuel Cells

Fuel cells are based on electrochemical reactions to produce electricity. By far the most common reaction is the combination of hydrogen and oxygen to produce electricity and water. The major advantage of fuel cells is their efficiency, which can be as high as 50 to 60 percent (electrical output/chemical energy input). They also have the potential for low emissions of objectionable gases; a fuel cell operating on hydrogen and air will produce only water vapor, and fuel cells operating with hydrocarbon fuels and air can be designed to produce no unburned hydrocarbons and no nitrogen oxides. The major disadvantages of fuel cells are their large size and weight, and their high cost. Fuel cells are currently used for power for space vehicles and for stationary power production. Substantial efforts have been devoted to developing fuel cells for automotive applications, and some demonstrations have been conducted in buses and automobiles. Fuel cells have not, however, reached the stage of practical application in automotive applications. More recently, there have been some preliminary investigations of the applicability of fuel cells for aircraft power plants.

There are several types of fuel cells, but only two appear to offer any potential for aircraft power plants, the proton exchange membrane (PEM) fuel cell and the solid oxide fuel cell (SOFC). The PEM fuel cell, discussed here, has received the most attention for mobile applications.

Figure 17 is a schematic of the basic PEM fuel cell. Gaseous hydrogen is supplied to the anode, where it is catalytically dissociated and ionized. The ionized hydrogen atoms (protons) enter the membrane, giving the anode a negative charge and polarity. Oxygen (in the air) is supplied to the cathode, where it is catalytically dissociated and ionized and reacts with water to produce negatively charged hydroxyl ions (OH^-) that enter the membrane. In the membrane, the protons and hydroxyl ions combine to form water. As long as hydrogen and oxygen are supplied, the cell will produce electric power (and water and heat). PEM fuel cells operate at a temperature on the order of 200^0 F, and generally at pressures of 2 to 3 atmospheres. Representative operating output of a single cell is on the order of 0.7 volts with a current density of 1 amp/cm^2.

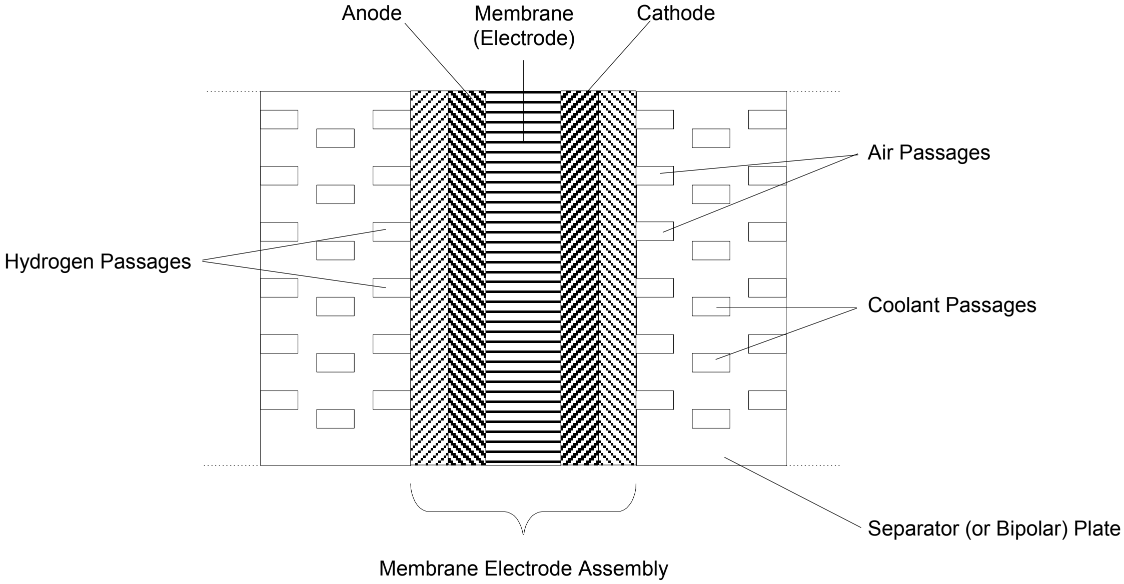


Figure 17. PEM Fuel Cell Schematic

Figure 17 also shows the basic construction of a unit cell, consisting of a membrane-electrode assembly and a separator plate. The separator plate, also called a bipolar plate, contains the passages for both hydrogen and air, as well as a coolant to remove waste heat. In some constructions, a separate coolant plate is used for cooling. The typical thickness of a cell is 0.2 inch or less, of which more than 90 percent is associated with the separator plate. For practical power production, cells must be connected in series to obtain a reasonable voltage level; this is accomplished by stacking individual cells end-to-end so that they are in good electrical contact with each other. The cells are held together by means of tie-rods.

For a self-contained power unit, some auxiliary systems are required:

- *Air management.* For cells that operate at elevated pressures, a compressor, expander, and drive motor for the compressor are required.
- *Thermal and water management.* This may include a liquid cooling system involving pumps and radiators.
- *Controls.*

- *Reformer.* If a hydrocarbon fuel is the primary fuel, then a reformer of some sort is required to extract hydrogen from the fuel.
- *Drive motor and propulsor.* For propulsion applications, a main drive motor and a propulsor of some sort (fan or propeller) are required.

A major effort to develop fuel cells for automotive systems was undertaken as part of the Partnership for the Next Generation of Vehicles program. This program set aggressive targets for automotive systems; the 2004 targets for an integrated system (excluding power conditioners and propulsion drive motors) were a specific power of 300 watts/kg (0.18 hp/lb) and a part power efficiency of 48 percent. Such power requires a specific power of the fuel cell stack alone of approximately 700–800 watts/kg (0.42–0.49 hp/lb). These specific power levels are much too low to be considered for aircraft applications.

Recently, NASA has initiated efforts to develop fuel cells for aircraft applications. One such projected power plant, based on the best-reported laboratory characteristics at the time, had the following characteristics [14]:

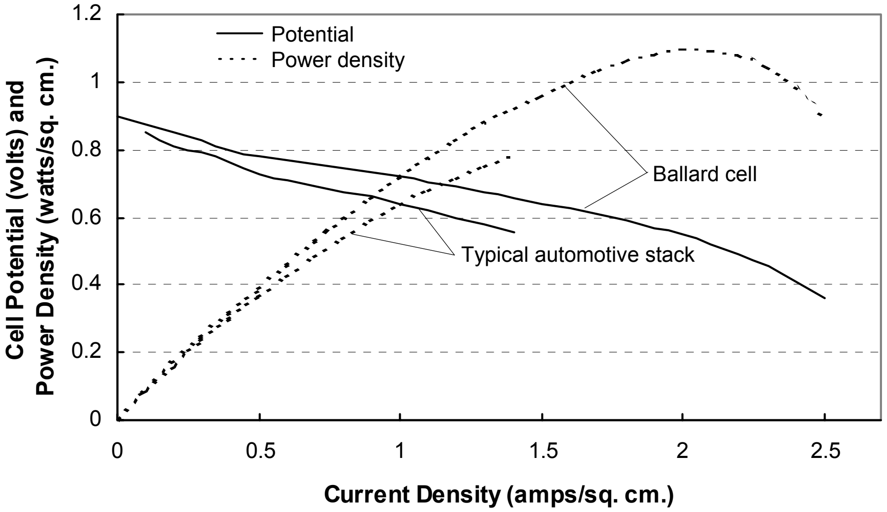
- Fuel cell power density: ~ 3 kw/kg (1.8 hp/lb)
- Cell width: 0.3 cm
- Motor power density: ~ 1 kw/kg (0.6 hp/lb)
- Power plant power density: ~ 0.75 kw/kg (0.46 hp/lb)
- Efficiency: ~ 40 percent
- Fuel: Hydrogen

The specific weight of this power plant (2.2 lbs/hp) is about 50 percent greater than that of conventional air-cooled spark-ignition aircraft engines (1.4 lbs/hp), and about 7 to 8 times greater than turboprop engines (0.25–0.35 lbs/hp). If this projected performance were to represent the best performance obtainable from a fuel-cell power plant, application to UAVs is unlikely because the fuel savings would not offset the increased weight of the fuel-cell power plant. This is true for both hydrogen fuel and hydrocarbon fuel. The use of hydrogen would, of course, pose significant logistical difficulties. The use of a hydrocarbon fuel requires the addition of a reformer to the fuel cell power plant; an optimistic forecast (see References [15] and [16], for example) for the specific power of a reformer is 1 kw/kg (0.6 hp/lb). Thus, the specific weight of the total fuel cell power plant increases from 2.2 lbs/hp to 3.8 lbs/hp—an order of magnitude heavier than turboprop power plants.

The notional C4ISR UAV (see Table 7) provides a basis for evaluating the tradeoff between fuel consumption and power plant weight. The minimum thrust required for takeoff is on the order of 5,000 pounds, corresponding to an aircraft thrust loading of 0.2. Assuming a nominal specific thrust at takeoff of 30 lb/lb/sec, the propulsive power required is about 4,400 hp. Assuming the electrical output of a fuel cell can be converted to propulsive power at an efficiency of 85 percent, the power required from a fuel cell would be about 5,200 hp. At a specific weight of 3.8 lbs/hp indicated above, this equates to a power plant weight of about 19,800 pounds, more than the 15,500-pound engine-plus-fuel weight of the gas turbine installation. Clearly this specific weight is much too high. If the fuel cell power plant efficiency is 40 percent, as compared to a typical gas-turbine efficiency of 30 percent (a TSFC of 0.65 at M = 0.8), then the fuel required by the fuel cell will be approximately 10,500 pounds as opposed to the 14,000 pounds required for the gas turbine. To be competitive with a gas turbine then, the weight of the fuel cell power plant cannot exceed 5,000 pounds, or a specific weight of about 1 lb/hp. These results depend somewhat on the baseline vehicle used; if the baseline vehicle had a higher fuel fraction (indicative of the desire for greater mission range), then a fuel cell power plant could be competitive at a slightly higher specific weight. The high baseline fuel fraction used here, however, provides a fair result.

The applicability of PEM fuel cells to UAVs thus requires further improvements in specific power beyond the 3kw/kg projection. One NASA target is a specific power of 7 kw/kg, and it is useful to examine how this might be achieved. Specific power levels can be increased in two ways: increasing the power density of the cell (output per unit active area) and/or decreasing the weight required per unit active area. The power density of a cell is determined by its voltage-current characteristics (also called a polarization curve). Figure 18 shows two such characteristics for PEM cells. The data for the typical automotive stack represent operation at about 3 atmospheres pressure and with pure hydrogen as the fuel. Neither the operating conditions nor the state of maturity for the Ballard cell are known; the fuel is pure hydrogen. It is this cell that is the basis for the 3 kw/kg projection in the preceding paragraph.

The general characteristic is a decreasing cell voltage with increasing current density. This decrease in voltage is due to various losses in the cell, and results in lower operating efficiencies. It is clear that there is a tradeoff between power density and efficiency—highest power densities are obtained at lower efficiencies, and thus also result in greater heat generation within the cell. Note that fuel cell stacks have somewhat lower performance than individual fuel cells; over the common range of current densities, the characteristics of the individual cells for the typical automotive stack are essentially the same as those in Figure 18 for the Ballard cell. To increase power density, it is necessary to shift the voltage-current characteristic upward and to the right. This shift requires a combination of improved electrical properties of electrodes and electrolytes and operation at higher pressures. The NASA target of 7 kw/kg is based on obtaining a cell power density of 2 kw/cm², and it is clear that substantial advances are required to achieve such a goal. As an illustration, Figure 19 shows two hypothetical voltage-current characteristics that would increase cell power density to 2 watts/cm² compared to those of the Ballard cell in Figure 18.



Sources: Ballard cell, Reference [10]; typical automotive stack, Reference [11].

Figure 18. Power Characteristics of PEM Fuel Cells

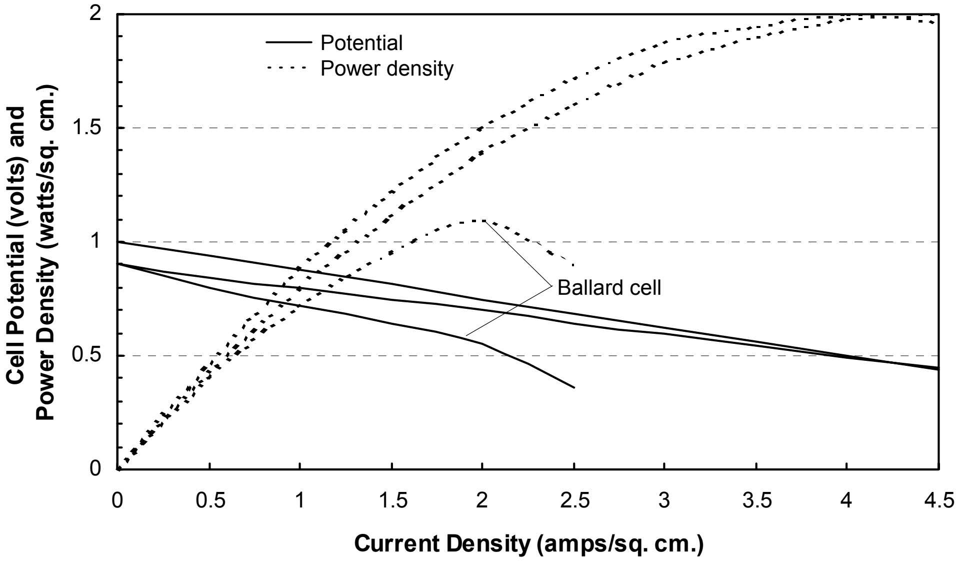


Figure 19. Notional Characteristics of 2 watts/cm^2 PEM Fuel Cells

Either of these characteristics represents a vast improvement over the Ballard cell (roughly doubling the current density at constant voltage), and no evidence has yet been found that such characteristics are achievable. Presumably operation at high pressures would be one ingredient, and this, of course, would introduce the additional weight and inefficiency associated with the turbomachinery required.

The 7 kw/kg target is also based on reducing the weight per unit active area from 0.37 g/cm^2 to 0.29 g/cm^2, based in large part on a 17 percent reduction in cell width, from 0.3 cm to 0.25 cm. Given the increased heat generation in the cell and the associated requirement for increased cooling, this reduction appears to be challenging indeed.

Should the 7 kw/kg fuel cell stack eventually prove to be obtainable, a resulting power plant suitable for UAV application would be roughly as follows:

- Fuel cell power density: 7 kw/kg (4.3 hp/lb)
- Reformer power density: 1 kw/kg (0.6 hp/lb)
- Motor power density: 1 kw/kg (0.6 hp/lb)
- Power plant power density: 0.47 kw/kg (0.28 hp/lb)

Without further advances in the power densities of reformers and motors, then, the specific weight of the power plant is 3.5 lbs/hp, which is still much higher than the 1 lb/hp needed to be competitive with the turbine.

The preceding explanation is not adequate for a complete assessment of possible future advances in fuel cells, but it does permit two conclusions relevant to the prospects for fuel cells for UAV applications:

- Compared to fuel cells for automotive applications, fuel-cell power plants for aircraft applications require roughly a factor of 4 increase in power density of the total system to be competitive with gas turbines. The possibility of accomplishing such an improvement appears to be problematic, given the challenges associated with increasing power densities of the basic fuel cells, the reformers to enable operation on a logistically acceptable fuel, and the propulsion drive motors. In any case, several years of effort will be needed to develop the technology to the point of demonstration.
- Fuel cell power plants are unlikely to be a significant consideration for the UAV applications considered here. At best, they may offer advantages for extremely long-endurance missions (≥ 50 hours, say). However, the number of vehicles likely to be required for such missions is small; hence, fuel cell power plants would need more widespread application to justify their development. At worst, the challenges

associated with increasing the power density to levels required for aircraft may not be overcome, and fuel cells would not be competitive with gas turbines for any UAV applications.

B. Pulse-Detonation Engines

Pulse-detonation engines (PDEs) represent an attempt to achieve the long-sought-after higher efficiency of constant-volume combustion, as compared to the constant-pressure combustion of the Brayton cycle. They come in many forms. An elementary concept that is easy to visualize consists of an inlet, an inlet flow control valve, a cylindrical combustor tube, perhaps an exit flow control valve, and an exhaust nozzle. The operation sequence is as follows. When the inlet valve is open, air flows into the combustor tube with fuel injection occurring simultaneously. When the tube is filled, a detonation wave is initiated at the upstream end of the tube and traverses to the end, in effect causing combustion at constant-volume conditions; the combustion gases then expand out the nozzle; the inlet air purges the combustor tube, and the sequence begins again. Other forms of the PDE include completely valveless devices. PDEs have potential as stand-alone propulsion systems and as a replacement for the high-pressure spool (high-pressure compressor, combustor, and high-pressure turbine) of gas-turbine engines.

A reasonable approximation to the ideal heat-engine cycle of the PDE is the Humphreys cycle; it consists of an isentropic compression, combustion at constant volume, an isentropic, unsteady-flow expansion to the combustor inlet pressure, and a steady-flow expansion to ambient pressure.[8] It is well known that this cycle offers higher ideal thermal efficiencies than the Brayton cycle employed by both gas-turbine engines and ramjets. For the record, for a perfect gas the relationships are, for the PDE cycle,

$$\eta_{id} = 1 - [(Q/c_v T_2 + 1)^{1/\gamma} - 1]/(Q/c_p T_1)$$

and for the Brayton cycle,

$$\eta_{id} = 1 - T_1/T_2$$

---

[8] Actually the detonation wave in the combustor results in combustion at effectively decreasing volume, as opposed to constant volume. A complete analysis of this cycle has been presented in Reference 9.

where T_1 is the ambient temperature, T_2 is the temperature after isentropic compression, and Q is the energy input per unit mass. These are displayed graphically in Figure 20.

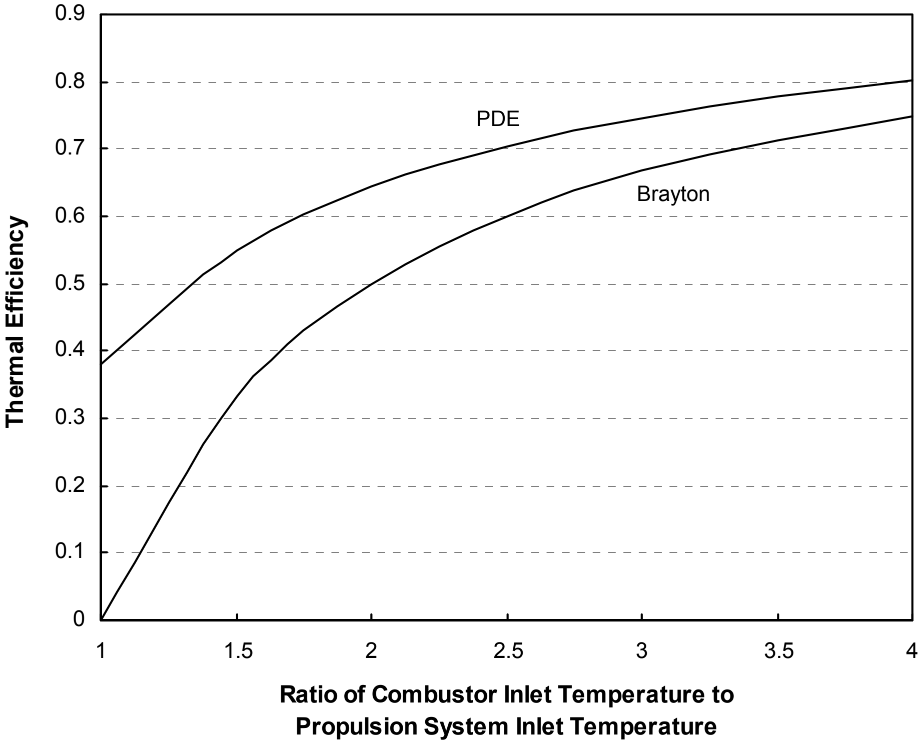


Figure 20. Ideal Thermodynamic Efficiencies of PDE and Brayton Cycles

Consideration of ideal heat engine cycles provides some insight into the potential of the PDE. The ideal cycle efficiency is primarily a function of the temperature ratio resulting from initial compression of the air. (In the stand-alone PDE concepts, this is accomplished in the inlet via vehicle motion). The curve for the PDE is for a heat input of 1,000 BTU/lbm, corresponding to an equivalence ratio of about 0.8. The results for a stoichiometric mixture are slightly higher.

The compression temperature ratio parameter is somewhat esoteric; for calibration purposes, if the compression is achieved solely by vehicle motion, a temperature ratio of 2 corresponds to a Mach number of 2.2, and a temperature ratio of 3 corresponds to a Mach number of 3.2. The corresponding isentropic compression pressure ratios are 11.2 for a temperature ratio of 2, and 47.3 for a temperature ratio of 3. A stand-alone PDE must achieve the temperature ratio through vehicle motion; a PDE used as a topping device can achieve the temperature ratio through a mechanical compression system. The two significant features of this figure are that the advantage in ideal efficiency of the PDE is largest where efficiencies are low, and that this advantage continuously diminishes as the compression temperature ratio increases.

Ideal efficiencies are of course only a general indicator of actual efficiencies. Real engines have losses associated with the compression, combustion, and expansion processes, as well as those due to leakage. These losses typically result in an actual thermodynamic efficiency of about 50 to 60 percent of the ideal efficiency (e.g., a gas turbine operating a temperature ratio of 2 will produce an actual efficiency of about 25–30 percent as opposed to the ideal 50 percent value). In propulsion applications, the overall system efficiency is further reduced by the propulsive efficiency (= $2/(1 + V_{ex}/V_o)$, where V_{ex} is the exhaust velocity and V_o is the vehicle velocity), reflecting the kinetic energy of the exhaust dissipated in the atmosphere. In short, the losses in a propulsion system are a greater determinant of the overall efficiency than is the ideal efficiency. The impact of these losses on PDEs are examined theoretically in Reference [17]. It is shown there that the expected differences in actual performance of PDEs and Brayton cycle engines are significantly smaller than the differences in ideal performance at temperature ratios greater than about 3.

The current status of the various PDE efforts is such that complete assessments cannot be made on the basis of actual experimental data: to date, no overall performance data exist for a complete PDE configuration at relevant operating conditions. Some proprietary performance models have been developed, but have not yet been completely validated with experimental data.

Fortunately for the purposes here, theoretical considerations of the ideal efficiencies and the potential impact of losses are sufficient to permit two conclusions regarding the potential of PDEs in UAV applications:

- *The stand-alone PDE is not suited for subsonic UAV applications.* Because the combustor-inlet-to-system-inlet temperature ratio would be at most 1.2, the stand-alone PDE has much lower efficiency (and much higher specific fuel consumption) than that obtainable from a gas-turbine engine; hence, the PDE is non-competitive for UAV applications.
- *Gas-turbine engines using PDE devices as the high-pressure system are unlikely to be a significant consideration for UAVs.* At best, such compound engines are far in the future and would need to be developed for an application more widespread than UAVs. At worst, such compound engines may not be competitive with conventional gas turbines, due to potentially excessive losses.

Appendix
Turbofan/Turbojet Requirements for Potential UAV Engines

There are three different engine specifications potentially applicable to various types of UAV engines: the commercial engine specification of the FAA [9], the DoD specification for engines for manned aircraft [10], and the Air Force specification for expendable UAV engines [11]. Table A-1 identifies the requirements of each of these specifications for turbofan/turbojet engines. For comparison purposes, the requirements of the two military specifications are arranged to correspond to the subject matter of the FAA specification. There is some subjectivity in this arrangement, but it does provide an indication of the similarities and differences among the specifications. Since the FAA specification is much more highly aggregated than the military specifications, it is not possible to ascertain from the table the specific military requirements that are also required by the FAA. In broad terms, most of the military requirements are also required by the FAA, although the methods of verification may be different.

Table A-1. Turbofan/Turbojet Requirements

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.4	Instructions for continued airworthiness				
33.5	Instruction Manual	3.1.1	Item and interface definition	3.1.	Item definition
		3.1.1.1	Interface and installation	3.1.1	Item diagrams
		3.1.1.3	Interface loads	3.1.2	Interface diagrams
				3.1.3	Mockup
		3.1.1.2	Installation hardware	3.8.1	Installation hardware
		3.1.1.5.1	Power lever and signal		
		3.1.1.5.2	Load demand command and signal		
		3.1.1.5.4	Fuel shutoff lever and signal		
		3.1.1.5.5	Lever torque		
		3.1.1.8	Drains and fluid collection devices		
		3.1.1.11	Starting drive train		
		3.1.1.11.1	Starting torque and speed		
		3.1.1.12	Thrust reverser interface		
		3.1.1.13	Exhaust system interface		
		3.1.1.14	Compatibility--Engine/Airframe		
		3.1.2.1	Dry mass of complete engine	3.6.1	Dry weight of complete engine
				3.6.1.1	Weight of fluids in operating engine
		3.1.2.2	Mass moment of inertia of complete engine	3.6.2	Mass moment of inertia of complete engine

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.5	Instruction Manual	3.1.5	Nameplate and product marking		
		3.1.5.1	Engine data plate marking		
		3.1.5.2	Critical parts identification and tracking	3.7.7	Critical parts identification and tracking
		3.1.6	Transportability	3.9.2	Transportability
		3.1.7	Interchangeability	3.7.1	Interchangeability
33.7	Engine ratings and operating limitations	3.2.1.1	Steady state performance	3.2.1	Performance ratings
		3.2.1.3	Performance computer program	3.2.2.1	Steady state performance digital computer program
		3.2.1.4	Performance retention	3.2.5	Performance retention
				3.2.7	Electrical performance
		3.2.2	Operating characteristics and limits		
		3.2.2.1	Operating envelope	3.3.1	Operating envelope
		3.2.2.2	Operating attitude and conditions	3.3.4	Attitude limits
		3.2.2.3	Starting		
		3.2.2.3.1	Ground starts	3.3.5.1	Engine starts
		3.2.2.3.2	Air starts		
		3.2.2.3.3	Starting limits		
		3.2.2.3.4	Starting procedure		
				3.3.5.2	Test starting/stopping
		3.2.2.3.5	Automatic relight		
		3.2.2.4	Stopping		
		3.2.2.5.1	Idle thrust/power (ground/flight idle)	3.2.4	Minimum thrust

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.7	Engine ratings and operating limitations	3.2.2.12	Gas path and measurement plane temp limits		
		3.3.1.1	Humidity		
		3.3.1.2	Fungus		
		3.3.1.3	Corrosive atmosphere	3.3.2.5	Salt air conditions
		3.3.1.4	Icing conditions		
				3.3.2.4	Temperature
33.8	Selection of engine power and thrust ratings				
33.1	Start-stop cyclic stress	3.4.1.5.2	Low cycle fatigue life		
33.2	Materials	3.1.3.	Materials, processes and parts		
				3.7.3	Major component list
		3.1.9.1	Parts list	3.7.5	Parts lists
		3.1.9.2	Assembly of components and parts	3.7.6	Assembly of components and parts
		3.1.9.3	Changes in vendors or fabrication process	3.7.2	Changes in design
		3.1.9.4	Standardization	3.7.4	Standard parts
		3.9.	Production facilities, capabilities and processes	3.7.11	Producibility
		3.10.	Production cost requirement		
33.2	Fire prevention	3.1.8.2	Fire prevention		
33.2	Durability	3.4.1.1	Design service life	3.6.6	Service life
		3.4.1.2	Design usage		
		3.4.1.3	Material characterization		
		3.4.1.4	Parts classification		

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.2	Durability	3.4.1.5	Durability	3.4.1.1	Durability/structural integrity
		3.4.1.5.3	Creep		
		3.4.1.6	Strength		
		3.4.1.6.1	Factors of safety	3.4.1.1.4	Engine pressure vessel/case design
		3.4.1.6.2	Blade and disk deflection	3.4.1.1.3	Blade and disk deflection
		3.4.1.6.3	Containment		
		3.4.1.6.4	Blade out		
				3.5.5	Main shaft bearings
		3.4.1.6.9	Pressure balance		
		3.4.1.6.10	Gyroscopic moments		
		3.4.1.7	Damage tolerance		
		3.4.1.7.1	Residual strength		
		3.4.1.7.2	Initial production and in-service flaw size		
		3.4.1.7.2	Flaw growth and inspection intervals		
		3.4.1.9	External surface foreign object damage		
		3.5.1.1	Reliability quantitative requirements	3.4.1	Engine reliability
				3.4.1.2	Storage
				3.4.1.3	Environmental stress screening
				3.4.1.4	Control of printed wire assembly
		3.5.2.1	Maintainability quantitative requirements	3.9.1	Maintenance
		3.5.2.1.1	Excluded maintenance functions		

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.2	Durability	3.5.2.3.1	Modules		
		3.5.2.3.2	Maintenance, inspection and repair cycle		
		3.5.2.3.2.1	Maintenance inspection techniques		
		3.5.2.3.3	Tools		
		3.5.3	Human performance and human engineering		
33.2	Engine Cooling	3.2.2.13	Surface temperature and heat rejection	3.6.3	Engine surface temperature and heat rejection
		3.2.2.13.1	Controls and external component limiting temp	3.6.4	Engine component limiting temperature
33.2	Engine mounting attachments and structure	3.1.1.4	Mounts		
		3.1.1.4.1	Main mounts		
		3.1.1.4.2	Ground handling mounts	3.8.2	Ground handling/engine mounts
		3.1.1.4.3	Engine stiffness		
33.3	Accessory attachments	3.1.1.10	Power takeoff		
		3.1.1.15	Control and Accessory component list?		
		3.4.2	Mechanical equipment and subsystem integrity		
		3.7.16	Gearbox	3.5.6	Accessory drive
33.3	Turbine, compressor, fan rotors	3.4.1.6.5	Overspeed and overtemperature	3.6.5	Overspeed limits
		3.4.1.6.6	Disk burst speed	3.4.1.1.2	Disk burst speed
				3.4.1.1.1	Rotor integrity

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Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	Title	Para	Title	Para	Title
33.3	Electrical and electronic engine control systems	3.3.3	Electromagnetic environmental effects (E3)	3.6.8	Electromagnetic interference and compatibility
		3.3.3.1	Electromagnetic interference		
		3.3.3.2	Intrasystem electromagnetic compatibility		
		3.3.3.3	Intersystem electromagnetic compatibility		
		3.3.3.4	Lightning	3.6.9	Electromagnetic pulse
		3.4.3	Avionic and electronic integrity		
		3.4.4	Software integrity		
		3.7.2	Control system	3.5.1	Controls
		3.7.2.1	Control system performance		
		3.7.2.1.1	Backup control		
		3.7.2.2	Control system adjustments		
		3.7.2.3	Overspeed protection system		
		3.7.4.1	Electrical power		
		3.7.4.1.1	Generator		
		3.7.4.2	Alternate electrical power		
		3.7.4.3	Electrical connectors and cables	3.5.3.1	Electrical connectors and cables
		3.7.4.4	Electrical bonding	3.5.3.3	Electrical bonding
		3.7.4.5	Ground isolation		
		3.7.4.6	Potting compounds		
		3.7.6	Engine monitoring system		
		3.7.6.1	EMS fault detection and isolation		
		3.7.6.2	On-board engine diagnostic function		
		3.7.7	Optical systems		

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Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.3	Electrical and electronic engine control systems	3.7.7.1	Fiber optic cables and connectors		
		3.8.1	Software performance and design	3.5.9.1	Design (computer resources)
		3.8.1.1	Built-in test and inspectability		
		3.8.1.2	Computer reprogramming		
		3.8.2	Spare resources		
33.3	Instrument connection	3.1.4	Fasteners		
33.6	Stress analysis	3.4.1.1	Design service life (rotors only)		
33.6	Vibration	3.4.1.8	Vibration and dynamic response	3.4.1.1.5	Vibration
		3.4.1.8.1	Vibration limits		
		3.4.1.8.2	Critical speeds	3.4.1.1.6	Critical speeds
		3.4.1.5.1	High cycle fatigue life		
33.7	Surge and stall characteristics	3.2.2.6	Stability	3.3.3	Stability
		3.2.2.7	Transients		
		3.2.2.10	Steady state and transient airflow	3.2.3	Airflow limits
		3.2.2.11	Inlet airflow distortion	3.3.3.1	Inlet airflow distortion limits
		3.2.2.11.1	Pressure and temperature rate of change		
33.7	Bleed air system	3.1.1.7	Bleed air interface		
		3.1.1.7.1	Customer bleed air contamination		
33.7	Fuel system			3.5.2	Fuel system
		3.7.3.1.1	Primary fuel	3.2.6	Fuel
		3.7.3.1.2	Alternate fuel		
		3.7.3.1.3	Restricted fuel		
		3.7.3.1.4	Emergency fuel		
		3.7.3.2	Fuel system performance (title)		

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Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.7	Fuel system	3.7.3.2.1	Fuel contamination	3.5.2.2	Fuel contamination
		3.7.3.2.2	Fuel system performance/external assistance	3.5.2.1	Fuel system performance/external assistance
		3.7.3.2.3	Fuel system performance/no external assistance		
		3.7.3.2.4	Fuel system performance/excessive fuel vapor		
		3.7.3.2.5	Fuel pump priming		
		3.7.3.2.6	Fuel lubricity		
		3.7.3.2.7	Fuel system performance/water saturated fuel		
		3.7.3.2.8	Fuel filter		
		3.7.3.2.9	Fuel flow limit		
33.7	Induction system icing	3.7.1	Anti-icing and de-icing system		
33.7	Ignition system	3.7.5	Ignition system	3.5.4.1	Main ignition system
		3.7.5.1.1	Carbon fouling		
		3.7.5.1.1	Water fouling		
33.7	Lubrication system	3.7.8	Lubrication system (title)	3.5.7	Lubrication system
		3.7.8.1	Lubrication oil		
		3.7.8.1.1	Oil pressure and temperature limits		
		3.7.8.1.2	Oil consumption limits		
		3.7.8.1.3	Oil flow interruption or depletion		
		3.7.8.2	Lubrication system components and features (T)		
		3.7.8.2.1	Oil reservoir		

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Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
33.7	Lubrication system	3.7.8.2.1.1	Oil reservoir external features		
		3.7.8.2.2	Oil drains		
		3.7.8.2.3	Oil filters		
		3.7.8.2.4	Oil debris monitors		
		3.7.8.3	Breather mist		
33.7	Hydraulic actuation systems	3.7.9	Hydraulic system		
		3.7.9.1	Hydraulic ground test provisions		
		3.7.9.2	Hydraulic system air removal		
		3.7.9.3	Hydraulic fluid filters		
33.7	Power or thrust response	3.2.1.2	Transient performance		
		3.2.2.7	Transients		
		3.2.2.7.1	Overshoot and undershoot		
		3.2.2.7.2	Droop		
		3.2.2.9	Reverse thrust ?		
33.7	Continued rotation	3.2.2.8	Windmilling	3.3.6	Engine windmilling capability
33.8	Safety analysis	3.1.8.1	Flammable fluid systems	3.7.9	Flammable fluid systems
				3.7.10	Flammable, toxic and hazardous materials
		3.1.8.3	Explosion-proof	3.5.3.2	Explosion proofing
		3.1.8.4	Combustible fluid drains ?		
		3.1.8.5	Air and gas leakage		
		3.1.8.6	Ground safety		
		3.1.8.7	Jet wake		
33.8	Foreign object ingestion	3.3.2	Ingestion capability		
		3.3.2.1	Bird ingestion		
		3.3.2.2	Foreign object damage		

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	Title	Para	Title	Para	Title
33.8	Foreign object ingestion	3.3.2.4	Sand and dust ingestion	3.3.2.2	Sand ingestion
		3.3.2.6	Armament gas ingestion		
		3.3.2.7	Steam ingestion		
33.8	Rain and hail ingestion	3.3.2.3	Ice ingestion	3.3.2.1	Ice ingestion
		3.3.2.5	Atmospheric liquid water ingestion	3.3.2.3	Atmospheric and water vapor ingestion
33.8	Fuel burning thrust augmentor	3.7.10	Exhaust nozzle system	3.5.8	Nozzles
		3.7.10.1	Exhaust nozzle external asymmetical air press loads		
		3.7.10.2	Vectoring nozzle		
		3.7.10.2.1	Vectoring nozzle angle and rate		
		3.7.10.2.2	Vectoring nozzle failure accommodation		
34.1	Standard for venting emissions				
34.2	Standards for exhaust emissions	3.6.1.3	Smoke	3.6.10	Smoke
		3.6.1.4	Gaseous emissions		
		3.5.2.4	Battle damage repair		
		3.6.1.1	Noise		
		3.6.1.2	IR radiation	3.6.11	Infrared and radar cross-section
		3.6.1.5	Fuel streaming and vapor puffing		
		3.6.1.6	Water vapor contrails		
		3.6.1.7	Radar cross section		
		3.6.1.8	Radar absorbent materials and coatings		

(Continued on the next page.)

Table A-1—*Continued*

14 CFR, Parts 33 and 34 (FAA)		JSSG 2007 (DoD)		AFGS-87271 (Air Force)	
Para.	**Title**	**Para**	**Title**	**Para**	**Title**
34.2	Standards for exhaust emissions	3.6.2.1	Ballistic weapons	3.7.8	Survivability, vulnerability and nuclear hardening
		3.6.2.1.1	Static structure		
		3.6.2.2	Nuclear weapons effects	3.6.9	Electromagnetic pulse
		3.6.2.3	Chemical and biological agent effects		
		3.6.2.4	Fuel ingestion effects		
		3.6.2.4.1	Fuel ingestion - steady flow		
		3.6.2.4.1.1	Fuel ingestion - cooling air contamination		
		3.6.2.4.2	Fuel ingestion - transient		
		3.7.11	Augmentation system		
		3.7.11.2.1	Water injection system fluid		
		3.7.12	Wash system		
				3.6.7	Storage life
				3.7.12	Corrosion protection
				3.9.3	Storage
				3.9.3.1	Temperature
				3.9.3.2	Humidity
				3.9.3.3	Fungus
				3.9.3.4	Temperature shock
				3.9.3.5	Acoustics
				3.9.3.6	Acceleration
				3.9.3.7	Vibration
				3.9.3.8	Shock

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Abbreviations

BTU/lbm	British Thermal Units per pound mass
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CFE	contractor-furnished equipment
DEW	directed-energy weapons
DoD	Department of Defense
E&MD	engineering and manufacturing development
FAA	Federal Aviation Administration
ft	foot
GFE	government-furnished equipment
IDA	Institute for Defense Analyses
hp	horsepower
hr	hour
kg	kilogram
kw	kilowatt
lb	pound
MRE	Multi-Role Endurance
NM	nautical mile
OUSD(AT&L)/S&TS	Office of the Under Secretary of Defense (Acquisition, Technology and Logistics)/Strategic and Tactical Systems
PDE	pulse-detonation engine
PEM	proton exchange membrane
RDT&E	research, development, test, and evaluation
sec	second
SLS	sea-level static conditions (0 altitude, 0 Mach)

SOFC	solid oxide fuel cell
TSFC	thrust-specific fuel consumption
UAV	unmanned air vehicle
UCAR	Unmanned Combat Armed Rotorcraft
UCAV	Unmanned Combat Air Vehicle
URSTAR	Unmanned Reconnaissance, Surveillance and Target Acquisition Rotorcraft

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14. ABSTRACT
IDA examined similarities and differences between gas-turbine engine requirements for manned and unmanned air vehicles (UAVs) and identified needs for technology development and engine development for two classes of UAVs: Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) UAVs and Unmanned Combat Air Vehicles (UCAVs). We found the potential market for UAVs similar to that for manned aircraft, but current efforts are generally exploratory and procurement quantities are uncertain. Advanced engines will payoff for UAVs, with specific fuel consumption having the highest impact, followed by thrust/weight ratio and engine procurement cost. It follows that technology directions for UAVs are similar to those for manned aircraft. Engines for UAVs do not pose any unique technical problems necessitating the development of a new engine, and hence a significant system buy will be needed to obtain the benefits of a new engine and offset the development cost. Minor modifications to new or existing transport engines will be preferred for long-range C4ISR applications. Significantly modified or new engines will be preferred for UCAV applications, but questions about the possibility of a common Navy-Air Force engine and related procurement-quantity issues should be answered before any commitment is made to engine development.

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