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TITLE: The Development and Operational Challenges
of UAV and UCAV Airbreathing Propulsion

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The Development and Operational Challenges of UAV and UCAV Airbreathing Propulsion

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INTRODUCTION: There are a large number of Unmanned Aerial Vehicles (UAVs) throughout the world performing a variety of functions. The variety of conditions under which they operate, e.g., speed, altitude, endurance, VTOL, payload etc. impact or limit the type and size of propulsion system needed.

This paper will define the various UAV categories and will characterize the types of engines and propulsors available for them. The variability of design features and their effect on characteristics will be shown. The effect of propulsion system trades on total system capability will be discussed.

CATEGORIZATION OF UAV's: Various organizations have used different categories to distinguish various types of UAV's. These categories have varied between organizations and at different times even within one organization. In addition, these categories often related to the usage of the UAV (e.g. Strategic or Tactical) or organizations using them (Corps or Platoon) rather than the items that affect propulsion needs.

For the purpose of this paper we have chosen to categorize UAV's into five discrete categories representing five diverse types of propulsion requirements. We have named these categories **Local, Regional, Endurance, Quick Look,** and **UCAV** (Uninhabited Combat Aerial Vehicle).

The **Local** category of UAV is most challenged by the fact that the equipment must be small, easily supported and potentially expendable. It is intended to be operated by a small group of soldiers with perhaps only one or two vehicles in a very mobile, volatile environment. There would be no time for extensive setup or maintenance. The equipment must be capable of being moved quickly and be economical enough that it could be willingly abandoned, if necessary. Figure 1 illustrates this category pictorially.

The propulsion challenges for the Local category of UAV are:

a) Compactness / Portability
b) Efficient low power class engine
c) Light weight
d) Minimum support equipment
e) Low cost

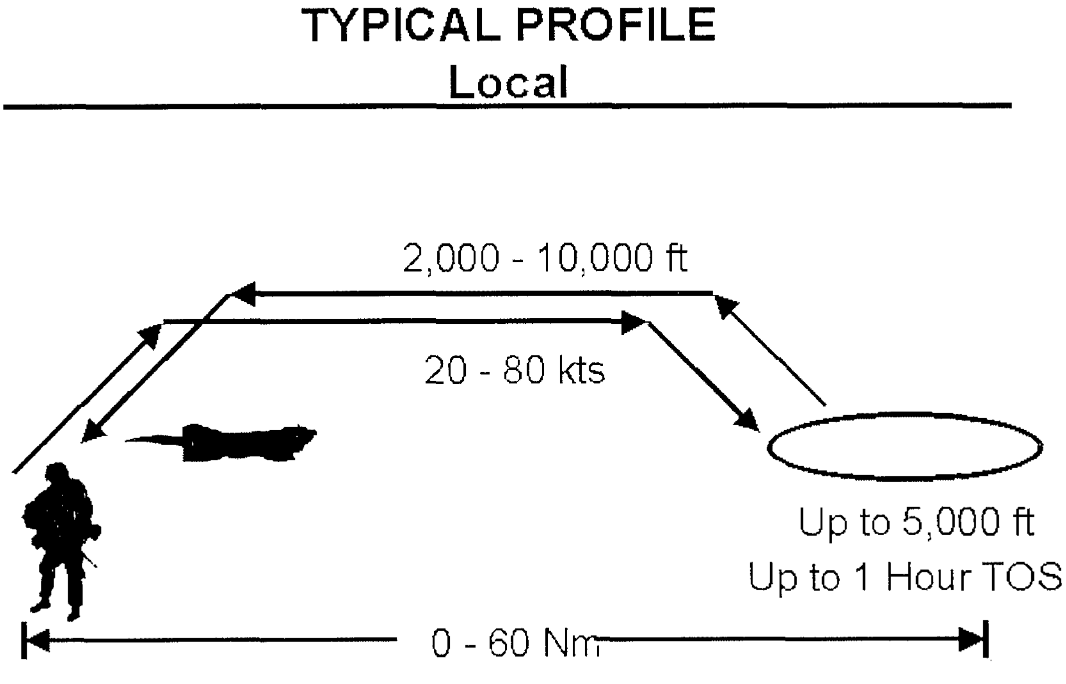


FIGURE 1

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

TYPICAL PROFILE
(Regional - Land / Ship Based)

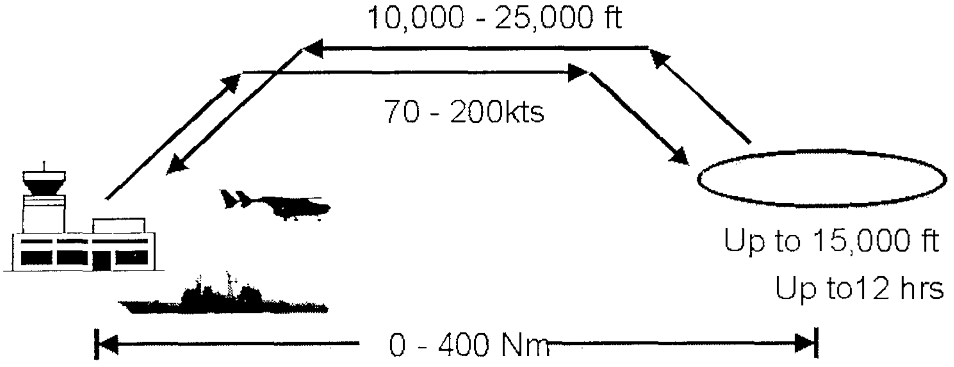


FIGURE 2

The **Regional** category is broken into two subcategories based upon the operating bases. The operating range, endurance, altitude and payloads are similar but the operational bases necessitate some differences in propulsion. Figure 2 illustrates this category pictorially.

The **Regional/Land based** subcategory is assumed to have a semi-fixed operating base with support and facilities. As such, it could have greater capabilities than the local category. Missions could be longer and, even though restricted to a region for which that organization is responsible, could be rather long range thus necessitating good propulsion reliability. A moderate length runway can be assumed to be available. Even though the facility is semi-fixed it is still assumed to be within a hostile military environment so that simplified maintenance and operation with commonly available battlefield fuels is important.

The propulsion challenges for the Regional / Land based category of UAV are:

a) High fuel efficiency at cruise and loiter
b) Operation with battlefield fuels
c) Simplified maintenance / modularity
d) Reliability
e) Low cost

The base for the **Regional / Ship based** subcategory is assumed to be aviation capable ships. This includes ships which have only helicopter capability. This will then necessitate a VTOL capability. This VTOL capability will demand a high power to weight ratio for the propulsion system since the vehicle will be lifted off the deck by virtue of brute force from the propulsion system with no wing to provide lift multiplication. Missions are relatively long duration and long range. The possibility of retrieval in an ocean environment is minimal. Therefore high propulsion reliability is necessary. The operations must fit within the normal shipboard routine and capabilities. Simple maintenance and operations with fuels normally carried on board the ship are mandatory.

The propulsion challenges for the Regional / ship based category of UAV are:

a) VTOL capability
b) Ship operational compatibility
c) Operation with shipboard fuels
d) Simplified maintenance / modularity
e) Excellent power to weight
f) Reliability
g) Low cost

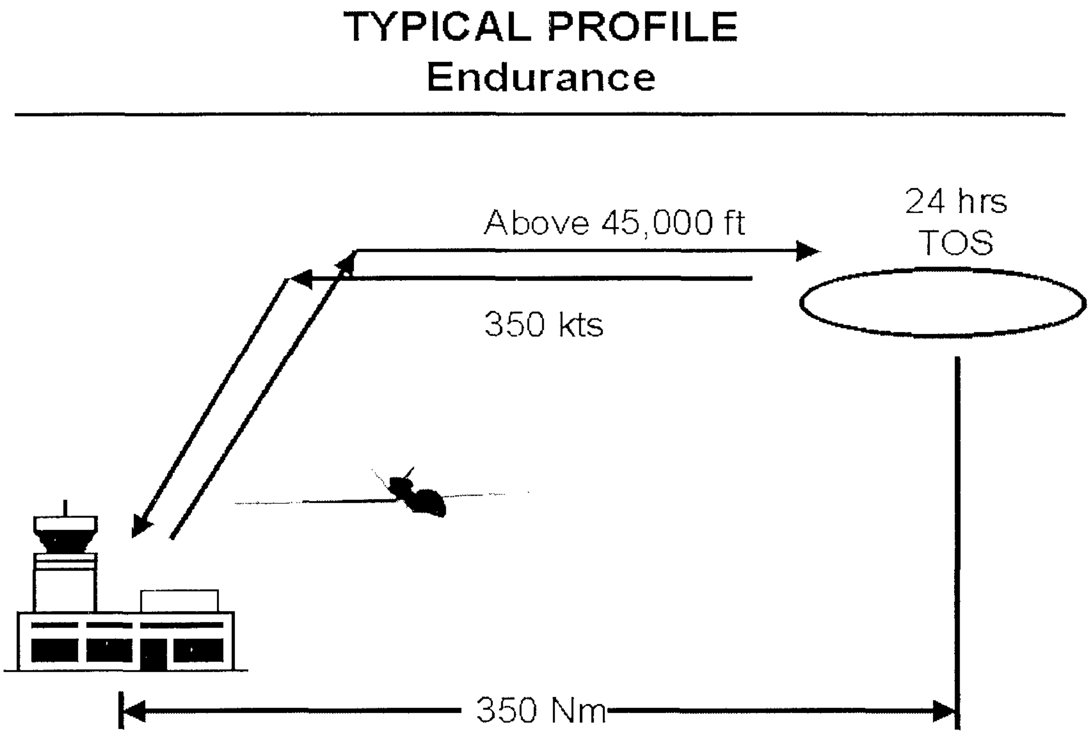


FIGURE 3

While the very title of the **Endurance** category tells us that high altitude and fuel efficiencies are required, reliability and good climb performance are also necessary even though not as immediately obvious. Reliability is important because the system could very well be very far out and at high altitude to achieve a mission. Large quantities of time, effort and money have been expended on getting the vehicle on station. A propulsion system failure in mid mission results in a loss of all this expended effort as well as the aborting of a mission that perhaps was relevant only at that specific time. The loss of the vehicle is also virtually assured.

Good climb performance is necessary not only because the mission is performed at high altitude but because the vehicle will be heavy with fuel at the beginning of the climb due to its planned long mission. Figure 3 illustrates this category pictorially.

The propulsion challenges for the Endurance category of UAV are:

a) Excellent mission reliability
b) Excellent fuel efficiency
c) High altitude capability
d) Good climb performance
e) Low cost

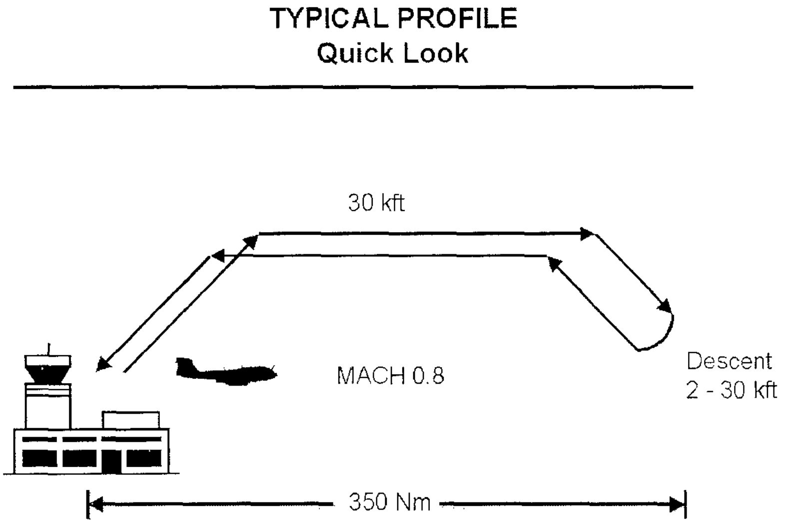


FIGURE 4

The **Quick Look** category is essentially an unmanned version of a fighter/reconnaissance type aircraft. While high thrust to weight and good efficiency at high mach number are characteristic of any high performance fighter aircraft these must be achieved at lower cost and with simpler maintenance than a fighter. The prime reason for this is that if it cannot be achieved at lower cost with simpler maintenance, why not just use a manned fighter type aircraft for reconnaissance as has been done since WWI ? It must be remembered, however, that the same question was asked about cruise missiles. The question was answered with low cost expendable engine technology which is very relevant to this category. Figure 4 illustrates this category pictorially.

The propulsion challenges for the Quick Look category of UAV are:

- a) High thrust to weight
- b) Good efficiency at high mach number
- c) Simplified maintenance / modularity
- d) Reliability
- e) Low cost

As generally envisioned today, the primary **UCAV** challenge will be the same as for any modern high performance military aircraft, i.e. high thrust to weight. The unique challenge in the UCAV, however, is the fact that this system is stored for most of its life rather than constantly in use for training missions.

Another challenge which could exist is the capability to withstand higher maneuvering loads if the designers choose to take advantage of the fact that there would be no pilot physiological limitations. Figure 5 illustrates this category pictorially.

The propulsion challenges for the UCAV are:

- a) High thrust to weight
- b) Storage capability (wooden round)
- c) Maneuvering load capability
- d) Low cost

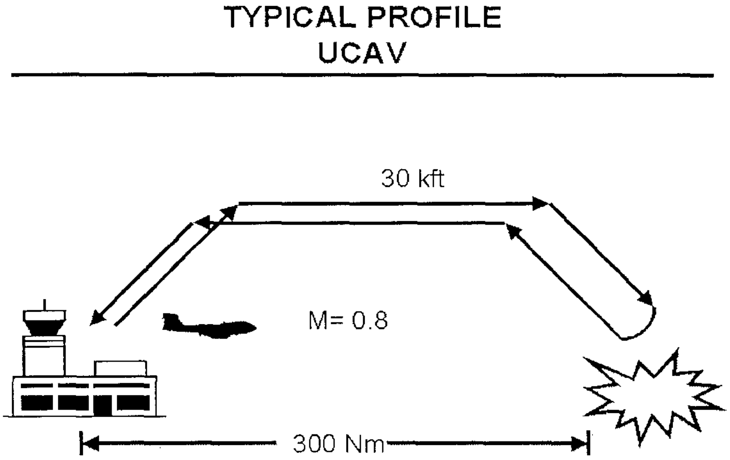


FIGURE 5

SYSTEMS ENGINEERING: This paper will illustrate the many options in propulsion with their greatly varying characteristics. These variations enhance the ability of the systems engineering team to make productive tradeoff studies involving propulsion. The application of systems engineering assures a balanced influence of all required design specialties, resolves interface problems and performs trade studies. Using a systems engineering approach for propulsion selection is desirable because it lessens the probability of unexpected propulsion system modification or replacement after deployment.

The need for a systems engineering approach (i.e. clean sheet vs. off the shelf selection) involves continuous and selective trade studies in which the propulsion system will be stressed so that the *right* engine and propulsor is selected for the application. Systems engineering involves trade-off studies at each level in the development process. The process shown in figure 6 describes the type of propulsion solutions that will be developed at each level in the process.

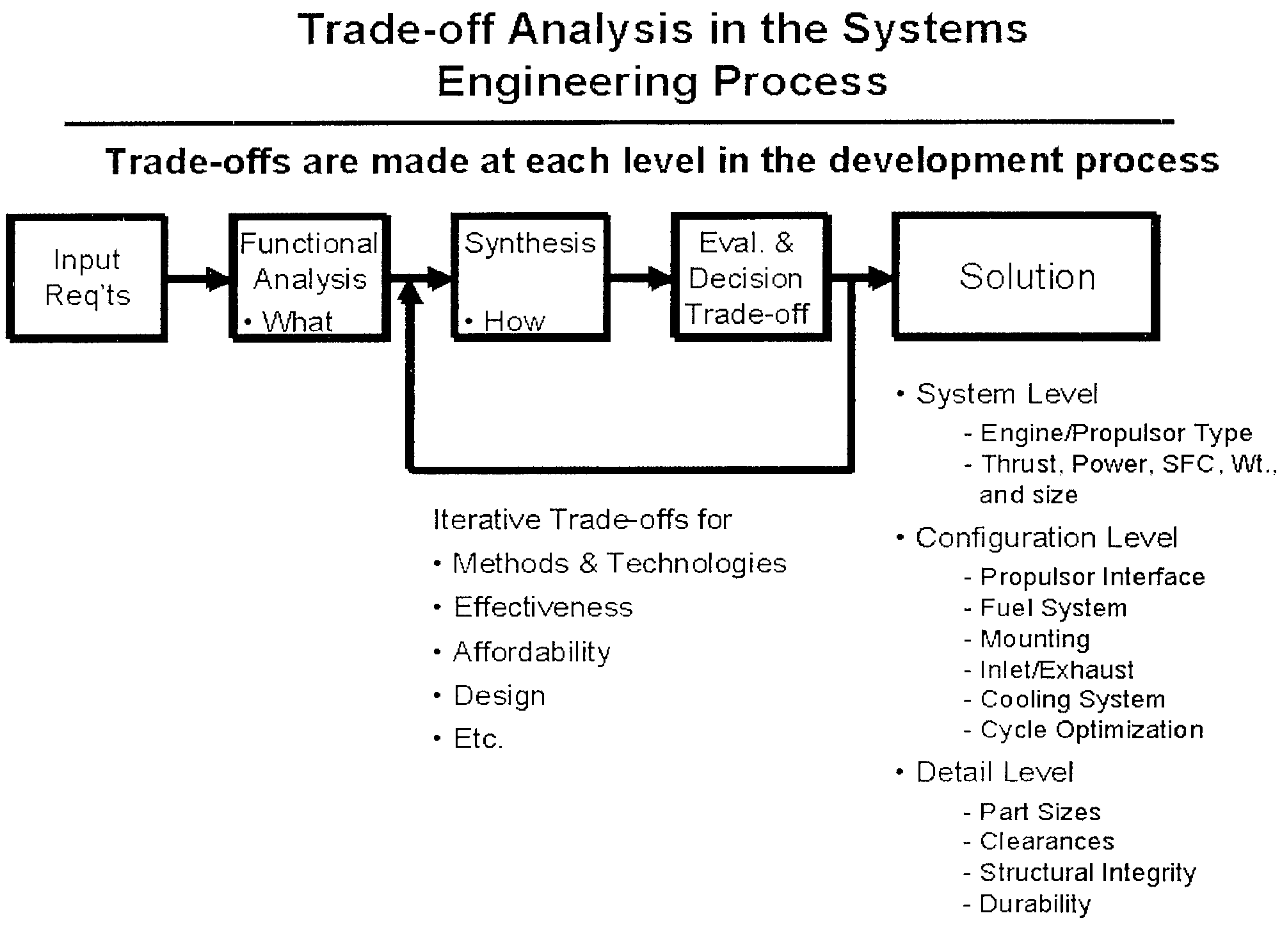
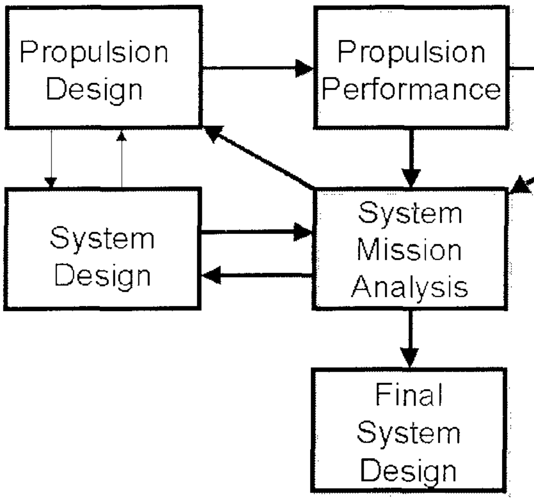


FIGURE 6

PROPULSION SELECTION
A SYSTEMS PROBLEM

A Typical process we use to identify the optimum propulsion system is shown below:



To better understand the system, let's be sure we understand the pieces of the system

FIGURE 7

Good System Engineering *requires* early propulsion trade studies. A typical process used in these studies for sizing and selecting the optimum propulsion configuration is shown in figure 7. The selection process is initiated by the overall system mission requirements which include mission profiles, operating envelope and environmental requirements. These parameters provide initial guidance for the class of propulsion system desired and may also aid in setting initial bounds on the range of design variables to be investigated. Analysis for a combination of independent propulsion system design parameters (such as disc loading, engine rotational speed etc.) initiates the process in the ***Propulsion Design*** block shown. A systematic variation of these variables leads to the definition of propulsion performance parameters such as thrust, fuel efficiency, weight and dimensions for each set of independent variables. These are integrated with the airframe configuration and design variables to develop aircraft figures of merit such as Take Off Gross Weight, Thrust-to-Weight ratio and wing loading and performance parameters such as landing distance, acceleration time, maneuver loads, and specific excess power. The propulsion system is selected based on the desired aircraft performance and design variables.

A comparison of the Global Hawk and Pioneer systems illustrates the advantages of applying early trade studies in the acquisition process. In the Global Hawk program, propulsion studies and characterizing tests were performed early in the program. The result was a low cost variant of a commercial engine.

In contrast, the Pioneer program was procured as a non-developmental item. No early propulsion trade studies and tests were conducted. The engine used in the application was procured "off-the-shelf". The result was that changes were required to the propulsion system early in the program to overcome carburetion and fuel system problems. In addition, when early attempts were made to replace the engine with one more suitable, the efforts and costs required to change an in service system were found to be overwhelming. Durability changes to the original engine are still being made after 13 years of operational use.

Propulsion System Operational Limits

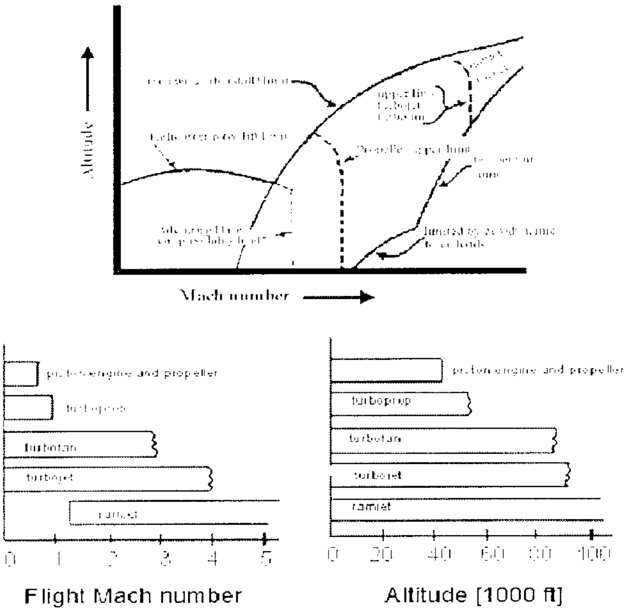


FIGURE 8

PROPULSION SYSTEM OPERATIONAL LIMITS: Figure 8 illustrates the operational ranges of various types of propulsion systems within envelopes of operational aircraft limits. The leftmost envelope represents a helicopter with a horizontal rotor propulsion system. The rotor propulsion system of a helicopter is limited in altitude by the control limits of the rotor pitch and decrease in the available engine power at altitude. The interaction of these effects yields the rounded top to the figure. Helicopter Mach number is limited by the compressibility effects on the advancing rotor blade.

The curved figure on the right represents fixed wing aircraft with propeller, fan and jet nozzle propulsion systems. Gross separation in fixed wing propulsion types (i.e. propeller vs. turbofan and turbojet) by speed are a result of compressibility effects on the propeller. Selection of the engine and associated propulsor (i.e. rotor, propeller, fan, nozzle) in overlapping operational conditions are based on trade studies that involve parameters such as disk loading, fuel consumption, various efficiencies etc. The propulsion system selection process will be discussed in more detail later in this paper.

PROPULSOR TYPES: A propulsion system consists of a **Propulsor**, the device that directly provides the moving force (thrust) to the vehicle and an **Engine** or prime mover. We will present all of these individually and then their various combinations.

Propulsors: There are four major types of propulsor devices. These devices and their definitions are:

Rotor- A device consisting of rotating airfoils which achieves lift and/or thrust depending upon its orientation. Propulsive thrust (and/or lift) is achieved by an increase in momentum of the air passing through it.

Propeller- A device consisting of airfoils rotating about an axis generally parallel with the direction of flight. Propulsive thrust is achieved by an increase of momentum of the air passing through it.

Fan- A device similar to a propeller but encased in a peripheral shroud thus permitting a higher momentum and pressure increase in a smaller diameter.

Nozzle- A device which converts the energy in a gas to velocity. Thrust is achieved by the momentum increase in the gas stream. (jet propulsion)

Engines: There are three major types of engines or prime movers used in UAV's. these engines and their definitions and subtypes are:

IC Engine- Intermittent Combustion engine. An engine that burns and exhausts its charge in repeating or intermittent cycles. The three major types of IC engines are:

SI Engine- Spark Ignition Engine. The common automotive type gasoline engine wherein the charge is throttled to vary power and a homogeneous charge is ignited by a spark or glow plug.

CI Engine- Compression Ignition Engine. The common Diesel engine wherein an unthrottled charge is introduced into the combustion chamber and compressed to a high pressure and temperature. Fuel is injected into the charge and autoignites. Power is controlled by varying the amount of fuel injected.

AI Engine- Assisted Ignition Engine. A low compression ratio engine which operates on the heavy fuels common to a Diesel engine. Since the compression ratio is not high enough for autoignition, a spark or glow plug or both is used to assist ignition. The lower compression ratio permits a lighter engine structure than a true Diesel.

2.) Gas Turbine Engine- An engine operating to the Brayton cycle. During this cycle air is compressed, fuel is added and burned at constant pressure and a turbine is finally used to provide energy for driving the compressor. The remaining energy in the hot gas is then used to provide shaft power or propulsive thrust. The three major types of aviation gas turbines are:

Turboshaft/Turboprop- A gas turbine engine which generates power by expansion of a vitiated fuel/air mixture through a turbine. The term turboprop is used to refer to a turbine integrated with a propeller. Turboshaft is used to refer to an engine which drives any other propulsor.

Recuperative Turboshaft- A turboshaft engine wherein heat is extracted from the exhaust gases and used to add heat to the process gases thus saving fuel. The Recuperative turboshaft engine is a special case of the turbine engine and, as such, is a slight modification to the Brayton cycle. This modification will be discussed later.

Turbojet/Turbofan- A turbine engine which achieves thrust by accelerating gases through a nozzle. (Jet Propulsion) In a turbofan a portion of the accelerated gas does not pass through the combustor. The Turbojet/ Turbofan engines are actually package propulsion systems composed of a nozzle or fan propulsor (or both) combined with a turbine prime mover.

3.) Electric- An electric propulsion installation generally consists of an electric motor as a prime mover, wiring, a power controller device, and an energy storage and / or generation device. Power storage is generally accomplished with a secondary battery. Energy generation is accomplished by means of solar cells or fuel cells. A hybrid propulsion system might consist of a fossil fueled engine which generates power for an electric propulsion system.

PROPULSOR CHARACTERISTICS: The primary characterizing parameter of an aircraft propulsor is its **Disk Loading** which is defined as the propulsive thrust divided by the cross sectional area of the propulsor disk through which the propelling fluid flows.

Figure 9 shows that as we progress from static to ever higher velocities the optimum disc loading increases. Ultimately, however each type of propulsor fails when the tip velocity of the airfoil approaches sonic speed. This is why transonic speeds had to wait for the development of the jet engine.

Notice that there is always an overlap. The reason for the overlap of each of the propulsors is that within each category there can be a variation in disc loading. That overlap and the fact that any system's missions will be flown at varying velocities illustrates the need for trades. The only place where the decision is clear is the static situation (hover). Here a large diameter rotor would be appropriate. But the minute any forward velocity is desired the situation again demands trades. The trades involving disc loading will be discussed in detail later.

Propulsors

Disk Loadings vs. Cruise Speed

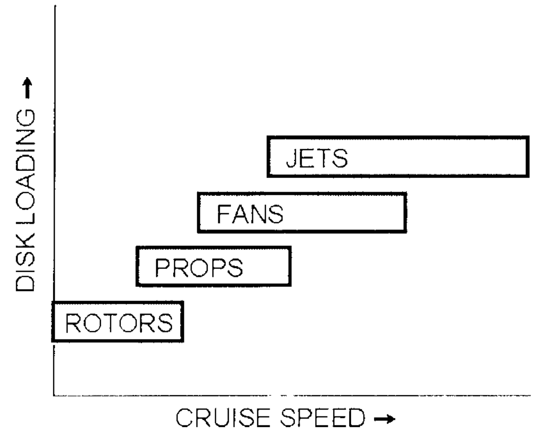
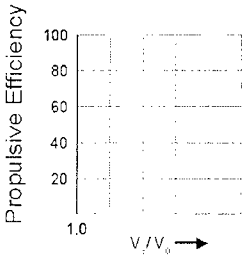


FIGURE 9

Propulsive Efficiency



where: $V_s / V = 1+(T/\rho V_0^2 A)$

Therefore at any given flight velocity and thrust

- Efficiency is greater with lower velocity increase
- Efficiency is greater with larger disk area
- Efficiency is greater with lower disk loading

FIGURE 10

Propulsive efficiency at any flight speed is dependent upon the ratio of the propulsor exit velocity to its inlet velocity as shown on figure 10.

Even though lower disk loadings produce higher propulsive efficiencies they have some very definite limitations at higher flight velocities. Figure 10 does not consider compressibility effects which are significant at higher Mach numbers. In addition, for a fan, the peripheral shroud on large fans becomes a significant source of drag.

Low disk loading devices will have a lower thrust to weight ratio which can be a significant detriment on high performance aircraft. Also low disk loading devices require low rotational speeds which may be incompatible with the prime mover unless a gearbox is added. This, of course, will increase the weight and complexity of the system. The conclusion, then, is that disk loading requires mission optimization trades to achieve the best system solution.

Engine Weights

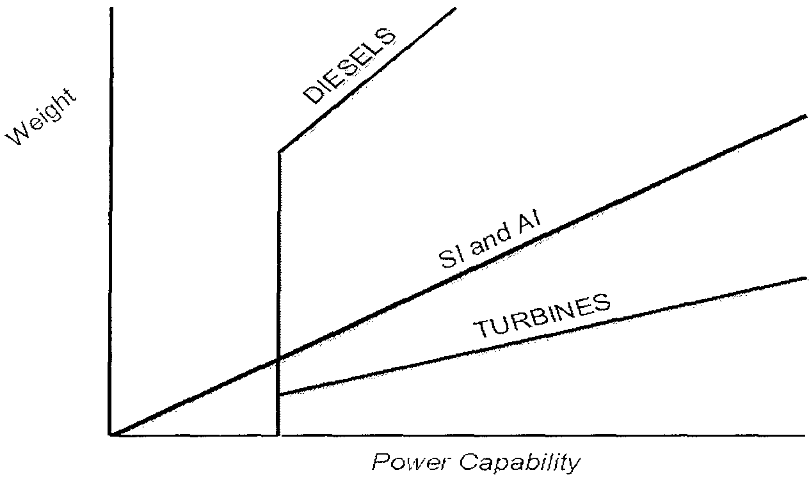


FIGURE 11

ENGINE CHARACTERISTICS: The primary engine characteristics subject to trades are **Weight, Power, Efficiency and Reliability**. The three different types of engines discussed and their subtypes all have very different characteristics.

Weight- The engine types vary markedly in their weight characteristics. This is dramatically illustrated in figure 11.

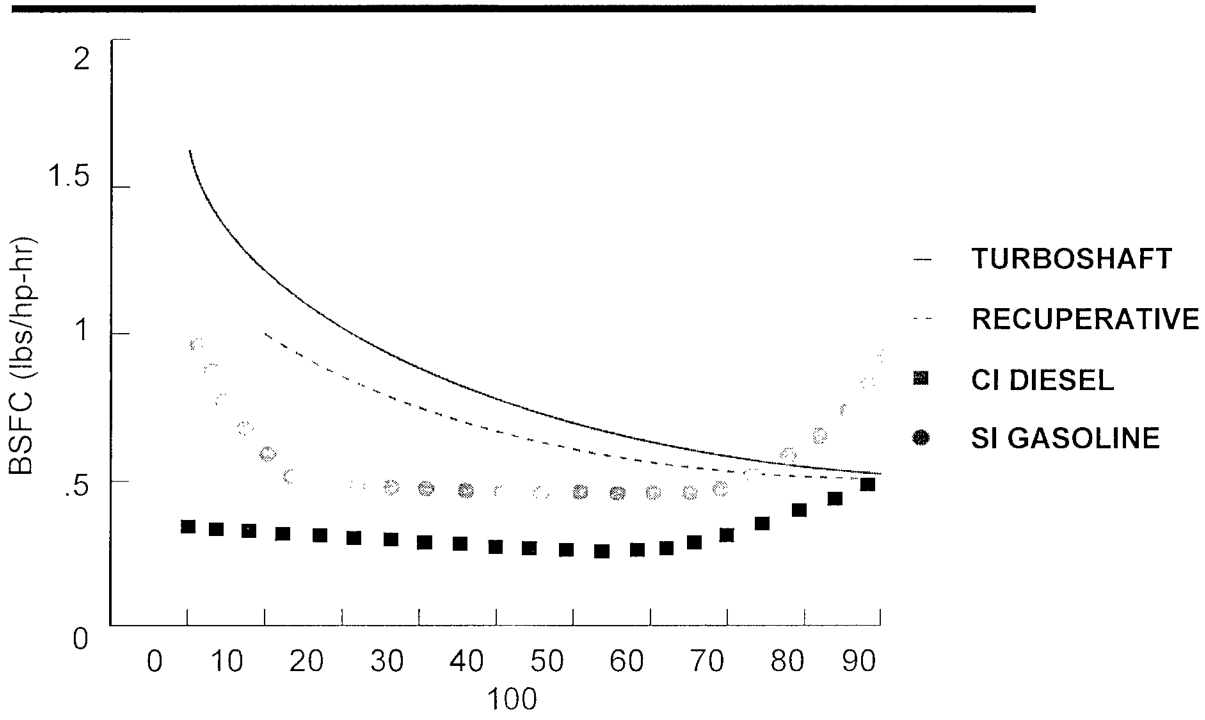
The lower horsepower limit for diesels and turbines shown on this slide is about 100 horsepower. This leaves the under 100 horsepower regime to Spark Ignition engines.

Power- The one power regime in which the SI gasoline engine has a clear advantage is in the very small sizes. These engines, because of their small combustion chamber sizes and high rotational speeds do not have a great susceptibility to detonation. For this reason they can be operated at high compression ratios and high Brake Mean Effective Pressure (BMEP). In addition, because of their favorable high area to volume ratio, cooling is relatively easy, again allowing operation at high BMEP with lightweight cooling schemes. Since there is no need for a direct fuel injection system, these system weights, which can only be made so small despite the engine size, are eliminated.

The two stroke air cooled type especially provides simplicity and light weight in the smaller sizes. These engines suffer in that they are not particularly durable, require frequent overhauls, emit an environmentally dirty exhaust, and use a real nuisance fuel which consists of gasoline mixed with special two stroke oils. Any Pioneer operator will verify all these attributes but, in spite of them, the Pioneer has served the U.S. Navy and Marine Corps well for over a decade.

Turbine engines are generally available over the 100 horsepower size, have the highest power to weight ratio of the fossil fueled engine types and are eminently suitable for most aviation applications.

Diesel engines are generally available in higher powers but their very low power to weight ratio makes them appropriate only when factors other than weight outweigh the extreme weight disadvantage.



Aircraft Shaft Power Engines
SFC Characteristics

FIGURE 12

Efficiency- When engine efficiency is discussed the term SFC (Specific fuel consumption) is generally used. This term represents the quantity of fuel burned per usable engine output. Lower SFC corresponds to higher efficiency. Figure 12 shows the power versus SFC characteristics of the various types of engines discussed. Of particular note is the extremely poor SFC of the turbine at part power conditions as contrasted to the very flat part power characteristics of the SI and CI engines. For this reason, SI and CI engines are often proposed as the most appropriate solutions for the type of mission where most of the fuel is expended at part power conditions. (e.g. the common UAV mission of long loiter times to obtain data). The overall good fuel efficiency of the CI engine is attributable to its high compression ratio.

The improved efficiency of the recuperative turbine engine is attributable to the recovery of heat from the turbine exhaust. This heat is normally wasted in a shaft power turbine. The cost is an increase in weight, cost and complexity which for some applications can be a good trade. The physical arrangement and its effect on the Brayton cycle is shown diagrammatically on figure 13.

RECUPERATIVE ENGINE
BRAYTON vs. RECUPERATIVE BRAYTON CYCLE

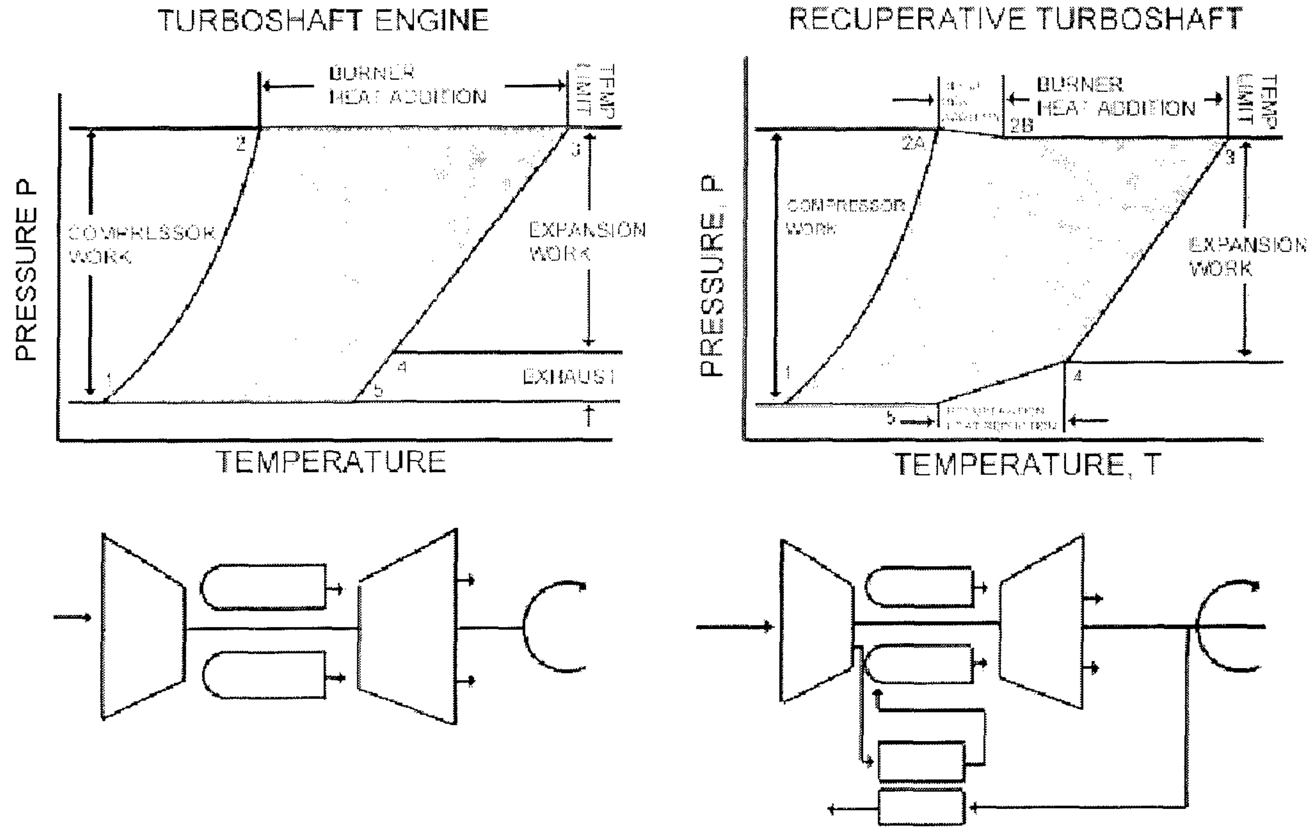


FIGURE 13

Recuperative turbine technology is not new. It is, in fact, old technology in stationary gas turbine powered electrical generators. Early on, the U.S. Navy had demonstrator engines built to study their use for long range patrol missions. The simplicity of operating with one or two engines shut down during loiter, which became standard P3 Orion practice, became the accepted solution and the aviation recuperative engine program died in the early 60's. Some tests were conducted on a small demonstrator recuperative engine at the U.S. Navy's propulsion test facility in 1994. Never have there been any studies which showed that a recuperative engine was not feasible in the 100+ horsepower class. The cost of full engineering development and production has often been the major concern. But cost should be only one of the factors in trade studies.

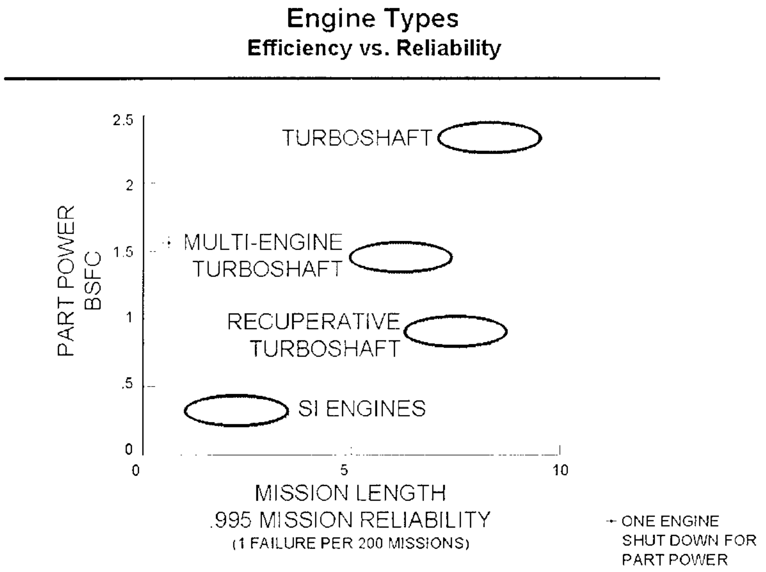
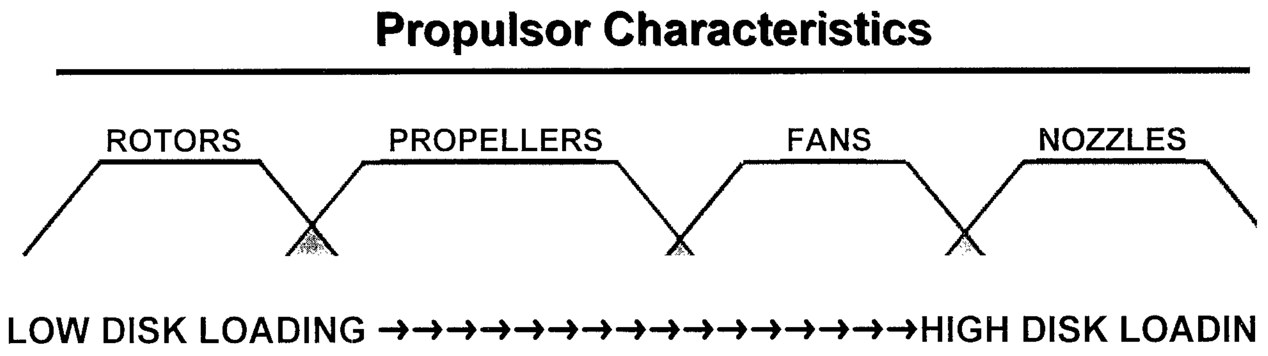


FIGURE 14

Reliability- Mission reliability is always important and is most difficult to achieve on longer missions. The longer missions require engines with very low SFC. Unfortunately engines which are characteristically the most reliable are those with the poorest SFC. This characteristic is shown on figure 14.

TRADES AND SELECTION FACTORS: All the propulsor and engine characteristics listed above become factors in the system trades and selection of a propulsion system. Attention must be given to both the propulsor and the engine component of the propulsion system. Finally the propulsion system as a package must be analyzed for its suitability to the intended application.

Propulsors- The factors used in a propulsor selection are shown in figure 15 as they relate to disk loading. It can be seen from this figure that the air vehicle flight speed, mission mix and physical configuration all affect the trades.



Large size (diameter)	Small diameter
Low rotational speed	High rotational speed
Good Static thrust	Poor static thrust
Rapid loss of thrust with forward speed	Good thrust at higher speeds
Good propulsive efficiency at low speeds	Poor propulsive efficiency at lo speeds

FIGURE 15

Shaft Power Engine Trades

	IC	Turboshaft	Recup Turbine	Multi-Turbine
BSFC	Best	Poor	Best	Best
Weight	Poor	Best	Best	Fair
Volume	Poor	Best	Poor	Best
Reliability	Poor	Best	Best	Best
Durability	Poor	Best	Best	Best
Cost	Lowest	High	High	Highest
Notes	1	2	2,3	2,4

1 - Smaller sizes require gasoline fuel
2 - Requires gearbox for propeller
3 - Limited aviation experience
4 - Based on P3 Orion experience

FIGURE 16

Engines- Figure 16 shows a summation of the engine attributes which could be the subject of trades in selection of the engine portion of the propulsion system. No one engine is perfect for all applications and for any single application compromises must be accepted in order to achieve the *necessary* mission requirements.

Propulsion System- The trade studies on the propulsors and engines is not complete until the propulsion system as a whole is considered. If, for example, a gas turbine is selected as a prime mover, the low rotational speed required by a low disk loading propeller could lead to the need for a reduction gearbox. The increase in weight and complexity of a reduction gearbox could negate all the efficiency advantages of the low disc loading device. A moderate disc loading fan may be an appropriate choice even though mission requirements may seem to indicate a propeller is the most **efficient** solution. The fuel savings achieved with the more efficient device may all be negated by the increased weight (and therefore drag) of the complete air vehicle.

SUMMARY: We have shown that UAVs can, for propulsion purposes, be divided into five categories. Each category has its unique propulsion needs. The five categories of UAVs are well served by the variation in characteristics of the many types of propulsion systems available.

Full advantage of the broad variation of propulsion characteristics can only be achieved with early propulsion trade studies and propulsion system testing to determine and verify the optimum system configuration.