Powerplants for Long-Duration Unmanned Aircraft

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During the past several years, considerable interest has been shown by the U.S. Department of Defense agencies in the development of long-duration unmanned aircraft. Many tactical missions have been identified that involve surveillance, reconnaissance, missile detection, missile targeting, and electronic countermeasures. The requirements for these missions vary, depending upon the payload characteristics, flight duration, and altitude. While both lighter-than-air and fixed-wing configurations have been considered, only the latter are discussed in this paper. The mission duration varied from several days to 4 years at altitudes of 47,500—110,000 ft. The aircraft operated in a recoverable mode, although some refurbishment was required after each flight. Six candidate propulsion systems are considered in this paper. Each provides an electrical power output that supplies the energy to propellers driven by electric motors. The energy conversion systems are limited to photovoltaics and an organic Rankine cycle electric power system. Energy sources included solar, chemical (i.e., propane), and nuclear (Po^{210} and Pu^{238} isotopes and a liquid-metal-cooled U-ZrH reactor) configurations. The advantages and disadvantages of each engine are discussed and estimated achievable aircraft altitudes are indicated as they relate to the mission duration and candidate engine type.

Introduction

THE use of unmanned aircraft has been a major activity in various U.S. Department of Defense (DoD) agencies for many years.[1] Typical missions have involved reconnaissance, surveillance, missile detection and targeting, electronic countermeasures, decoys, training targets, and radar and infrared signature simulators. These aircraft became known as remotely piloted vehicles (RPV). Both expendable and recoverable versions were developed. Depending upon the mission or application, these were usually short-duration vehicles. Propulsion was provided by propjet, turbojet, pulsejet, rocket and ramjet engines. In most cases, maximum altitudes were limited to approximately 60,000 ft.

In the last few years, the need has developed for high-altitude (up to 110,000 ft), long-duration (9 days to 4 years) platforms to meet new tactical objectives due to the emergence of various military threats from new missile weapon systems. For example, the U.S. Navy envisioned the need for multiple platforms operating at 68,000 ft, each equipped with radar.[2] Each platform would provide line-of-sight coverage over 300 n. mi. to protect the fleet against antiship missile attacks. More recently, ballistic missile defense technology includes consideration of of hypervelocity guns.[3] Use of an airborne optical surveillance system on a long-duration RPV (Fig. 1) is one approach being considered and unclassified applications exist. The various options available to DoD mission planners are presented in the following discussion that follows.

The engines considered are: 1) solar array/secondary batteries, 2) propane/organic Rankine cycle electric power system (ORCEPS), 3) solar array/propane/ORCEPS, 4) Po^{210} isotope/ORCEPS, 5) Pu^{238} isotope/ORCEPS, and 6) liquid-metal-cooled U-ZrH reactor/ORCEPS.

Powerplant Considerations

The four parameters of most interest to mission planners are payload mass, flight duration, vehicle speed, and altitude. These factors are paramount in determining the overall unmanned aircraft configuration and ultimately the required engine characteristics. There is a wide range of requirements for the various long-duration RPV applications under consideration. A typical set of requirements is provided in Table 1. As may be noted, both a propane combustor and an isotope heat source are listed for this application. However, for long-duration missions (approximately 4 months to 4 years) it is mandatory to employ a nuclear heat source or a solar array/battery system. For missions limited to several days, a chemically powered (i.e., propane) powerplant can be utilized if the engine weight can be kept to a minimum and its specific fuel consumption is low.

The equation used to determine flight endurance is the Brequet equation as follows:

$$E=\frac{\eta_p \times 778}{\mathrm{BSFC}}\left(\frac{(C_L)^{3/2}}{C_D}\right)\sqrt{\frac{\rho_{\mathrm{air}}S}{g}}\left(\frac{1}{(W_2)^{0.5}}-\frac{1}{(W_1)^{0.5}}\right) \quad (1)$$

where:

BSFC	= brake specific fuel consumption, lb/hp·h
C_D	= drag coefficient, 0.04 (typical)
C_L	= lift coefficient, 1.1 (typical)
C_L/C_D	= lift-to-drag ratio, 27.5 (up to 40-60 achievable)
E	= endurance of flight, h
S	= wing area, ft^2
W_1	= total initial vehicle weight (including fuel), lb
W_z	= total final vehicle weight (including residual fuel), lb.
η_p	= propeller propulsive efficiency, 0.8 (up to 0.85 – 0.88 achievable)
ρ_{air}	= density of air at altitude, slugs

This equation assumes a reduced throttle setting as the fuel is consumed. For a given set of vehicles and aerodynamic parameters, the most significant factor affecting long-duration operation is the BSFC. For the propane-powered engines (candidates systems 2 and 3), this value was estimated to be 0.40 lb/hp·h based upon an ORCEPS cycle efficiency of 27%. For the solar array/battery configuration (candidate system 1), operational duration is primarily determined by the battery cycle life and the depth of discharge (DOD) utilized. Solar cell degradation has been assumed to be negligible. The

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isotope powered configuration (candidate systems 4 and 5) operating life is a function of the half-life of the isotope employed. This is 134 days (~4.5 months) for Po^{210} and 87.7 years for Pu^{238}. Finally, for the nuclear-reactor-powered engine (candidate system 6), the vehicle operating duration is based upon the fuel burnup rate.

The required engine output power is a function of the vehicle configuration and the operating altitude. This is depicted in Fig. 2 for a 3000 lb total weight vehicle. For a powerplant output power of 13–75 kWe, achievable vehicle altitudes are 47,500–110,000 ft. These powerplant requirements are summarized in Table 1.

The inboard profile of the powerplant is shown in Fig. 3. The ORCEPS is the baseline energy conversion system for providing the electric power to the motor-driven propeller (candidate systems 2–6). However, the solar array/battery configuration (candidate system 1) provides electric power directly to the motor. Candidate system 3 utilizes a solar array to extend the operating time of the propane/ORCEPS by providing power during daylight operation.

A schematic of the ORCEPS power engine is shown in Fig. 4. The working fluid selected for this power conversion system is toluene (Monsanto CP-25). This fluid results in achieving a high energy conversion efficiency while staying well within the desirable operating region for cycle condensing temperature and pressure (Fig. 5). Typical cycle conditions are shown in Fig. 6. A more detailed description of the ORCEPS can be found in Refs. 4 and 5.

There are various fuels that could be considered for the chemically powered ORCEPS. Typical are those listed in Table 2. Propane with a high heating value of 21,788 Btu/lb, a density of 36.5 lb/ft^3, and a freezing point of $-306°F$ appears to be an excellent fuel for long-duration RPVs and was selected for use with the chemically powered ORCEPS. The heat of combustion of propane is 14% greater than for JP fuels. Hence, for the specified total vehicle weight and an assumed fuel fraction, a longer mission duration is achievable with propane. In addition, its higher inflammability limits (i.e., 9.35 vs approximately 1.0 for JP fuels) should permit operation at higher altitudes, although the determination of the magnitude is a fairly complex function of many additional parameters and beyond the scope of this paper.

Various isotopes are available as a heat source for the ORCEPS. These are depicted in Fig. 7. Density, half-life, and radiation emitter class are the key parameters in their selection. To minimize shielding weight, alpha emitters are to be preferred. Because Tm^{170} is a beta emitter, it was not considered for the application. Cm^{242} and Cm^{244}, while essentially classified as alpha emitters, also have slight traces of beta and gamma emissions. This would increase their shielding weights. Thus, Pu^{238} and Po^{210} were selected as attractive, minimum shield-weight isotope heat sources. Because of its long half-life (87.7 years), Pu^{238} would appear to be the most desirable for achieving long-duration operation. However, its energy density is only 0.56 W/g as compared to 79.5 W/g for Po^{210}. Hence, for achieving high thermal power output at minimum weight, Po^{210} is to be preferred. Both isotopes were considered for the long-duration RPVs because achievable altitude was as important a parameter as operating time.

A U-ZrH reactor was selected as a heat source because this energy source is very attractive for extremely long operation (i.e., 4 years). When combined with a low-peak cycle ORCEPS, this configuration has the potential for achieving high

Table 1 Typical long-duration RPV requirements

Vehicle	Powerplant
Operation	Propane combustor
9 days to 4 years on station	Isotope heat source (Po^{210} or Pu^{238})
75-200 knots forward speed	Organic Rankine cycle (CP-25)
3000 lb (total weight)	Electrical output power
Delivered shaft power of 13-75 kW	Variable speed outputs
47,500-110,000 ft altitude	Heat dump capability to load match to power variations on the isotope
Payload capability	Integral ram air heat exchanger to optimize performance
100-200 lb	
Optical to Em wide band and passive	In-flight startup as well as potential shutdown
	Minimum weight
	Largest output power possible with a single heat source

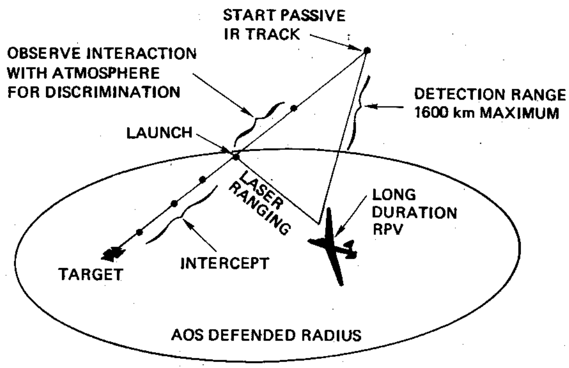

Fig. 1 Scenario for use of long-duration RPV with hypervelocity gun for ballistic missile defense.

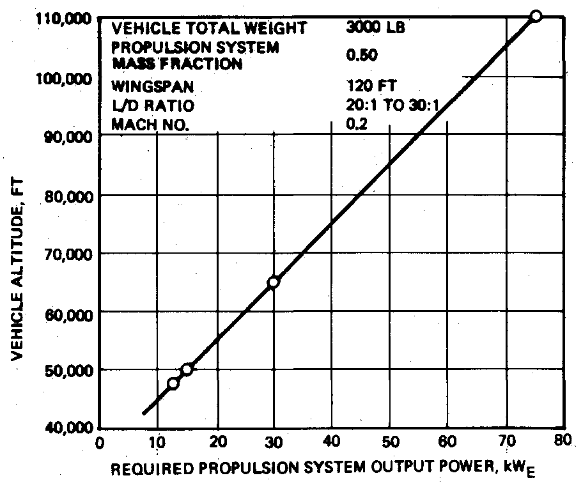

Fig. 2 Engine output power as a function of vehicle altitude.

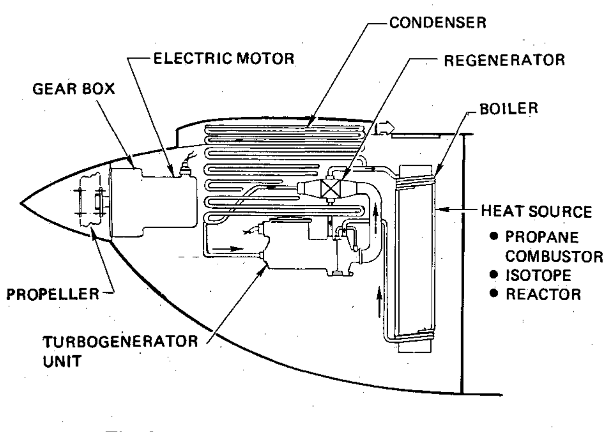

Fig. 3 Inboard profile of RPV powerplant.

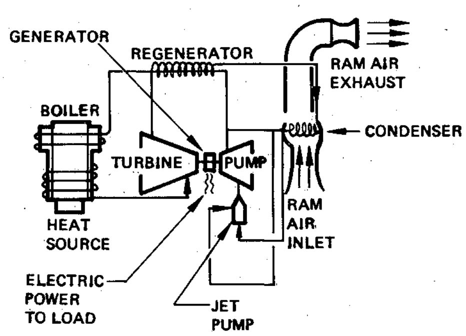

Fig. 4 Schematic of ORCEPS powerplant.

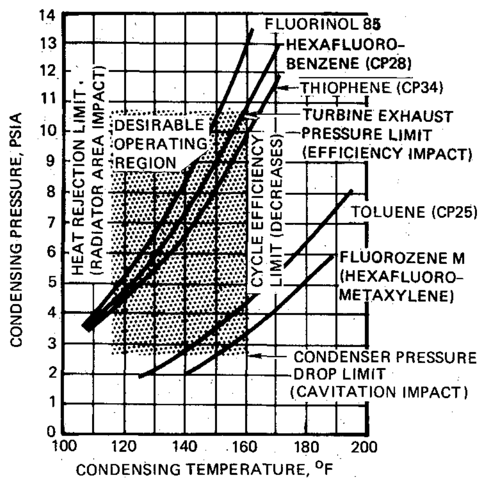

Fig. 5 Condensing temperature and pressure limits.

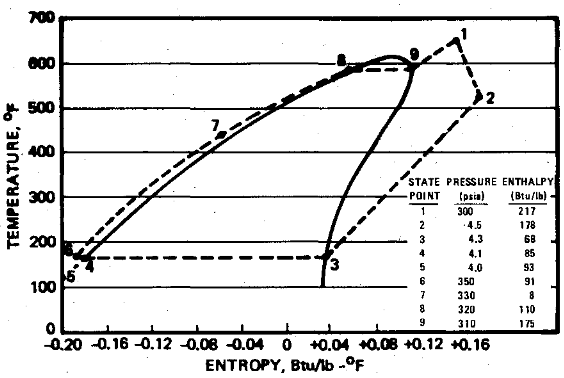

Fig. 6 Temperature-entropy diagram toluene (CP-25).

reliability. This reactor has an extensive technology base, having been previously developed by the Department of Energy/Atomic Energy Commission for the SNAP 2 (3 kWe) and SNAP 8 (35-50 kWe) space power system programs.

Finally, because a static energy conversion system also has the potential for high reliability and long operating life, a solar array/battery system (candidate system 1) was selected as a potentially attractive configuration. Planar, silicon cell, 2 mil solar arrays can achieve a specific power of 30 W/lb (33 lb/kWe). However, when combined with secondary batteries (i.e., nickel-cadmium) capable of operating at a 70% DOD and 600 cycles/year, the overall specific power of this system is reduced to approximately 10 W/lb (100 lb/kWe). Hence, this value was used in determining the propulsion characteristics of this system. When the solar array was used in conjunction with the propane/ORCEPS (candidate system 3), the higher specific power value of 30 W/lb was utilized.

Candidate Propulsion System Characteristics

In evaluating the various candidate propulsion systems, the two parameters of most interest to the military planners were altitude and duration. To determine this for a 300 lb total vehicle weight RPV, with a propulsion system mass fraction of 0.50, the achievable output power for each system was determined. The results of these analyses are summarized in Table 3. As may be noted, within the specified mass fraction constraint, the output powers varied from 13 to 75 kWe. The altitudes achievable with these various output powers can now be obtained from Fig. 2. These results are shown in Fig. 8.

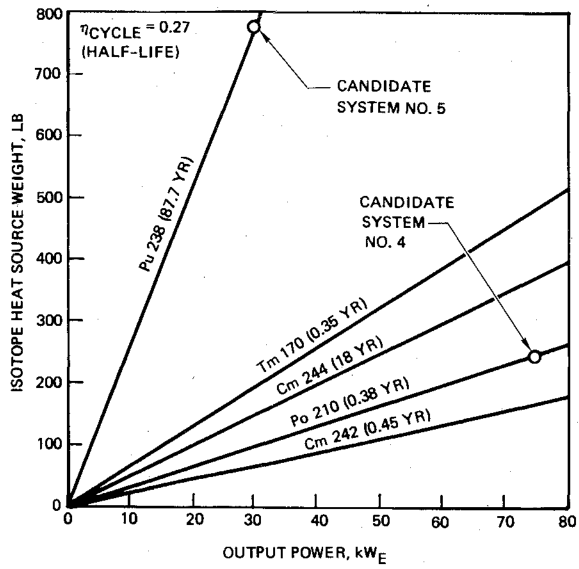

Fig. 7 Isotope heat source weights.

Table 2 Properties of fuels

Fuel	Heat of combus- tion, Btu/lb	Heat-sink limit temper- ature, °F	Heat sink, Btu/lb	Density, lb/ft³	Boiling point, °F	Freezing point, °F
Methane	21,500	1000[a]	1100	26.5[b]	−259	−296
JP (regular)	18,600	375	165	50	300	−65
Ethane	20,420	950	750	33.0[b]	−128	−298
Propane	21,788	850	700	36.5[b]	−44	−306
JP (gold plated)	18,700	700	365	50	300	−65
Hydrogen	51,570	1000[a]	4900	4.3[b]	−423	−435
Nitrogen	—	—	—	50.5[b]	−321	−346
Oxygen	—	—	—	71.5[b]	−297	−362

[a] Fuel limit, ~1200°F for methane; no limit for hydrogen. [b] Density at normal boiling point.

The solar array/battery system can achieve an altitude of 50,000 ft and operate for 1 year. The battery cycle life is the main factor in limiting RPV operating duration. This appears to be a very attractive candidate system. However, 2 mil silicon cells are fairly fragile. High air turbulence during the ascent portion of the operation could lead to cell or cell interconnect failure. The effects of jet stream on the high-aspect-ratio RPV wings may cause fluttering, which may also adversely affect the solar array structure. Finally, the solar array must be continually oriented toward the sun. This could place severe restrictions upon the maneuverability of the vehicle.

The propane/ORCEPS eliminates the operational problems associated with the solar array/battery system but at the expense of a greatly reduced mission duration (i.e., 9 days) and a lower achievable altitude (47,500 ft). However, for many applications, 9 days may be an acceptable period. The solar array augmented propane/ORCEPS systems provide a small increase in operating time (12 days). However, the potential problems associated with the use of the solar array appear to offset the advantage of the small increase in the vehicle operating duration. The Po^{210} isotope/ORCEPS provides a dramatic increase in achievable altitude (110,000 ft) and is capable of up to 4 months operation. The main drawback to this system is the large amount of isotope required, which, because of the short half-life of Po^{210}, necessitates close coordination between the isotope heat source manufacture and its use if the full operating duration is to be achieved. It is also obvious that long-term storage of the RPV with this powerplant would not be practical, thus imposing serious operational constraints. The Pu^{238} isotope/ORCEPS is attractive if very long operating periods (i.e., 2-4 years) are desired. However, because this system is heavier than the Po^{210} isotope/ORCEPS, its achievable altitude is only 65,000 ft. Additional shortcomings of this system are limited isotope availability, high isotope costs, and potential political/safety issues associated with the use of special nuclear materials.

The U-ZrH reactor/ORCEPS is considerably less costly than the Pu^{238} isotope/ORCEPS system. In addition, there are no problems associated with fuel rod material availability. Up to 4 years operation is possible with this system but because of the heavy weight resulting from the use of a 4π shield, the achievable altitude is only 50,000 ft. Political/safety issues are also a potential problem associated with the use of this system.

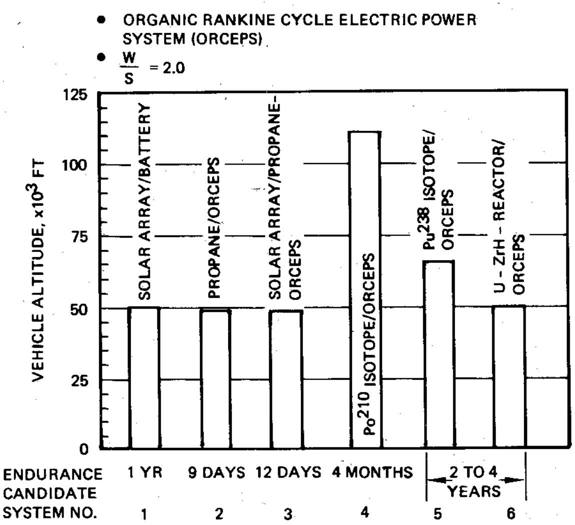

Fig. 8 Long duration unmanned aircraft—candidate propulsion system comparisons.

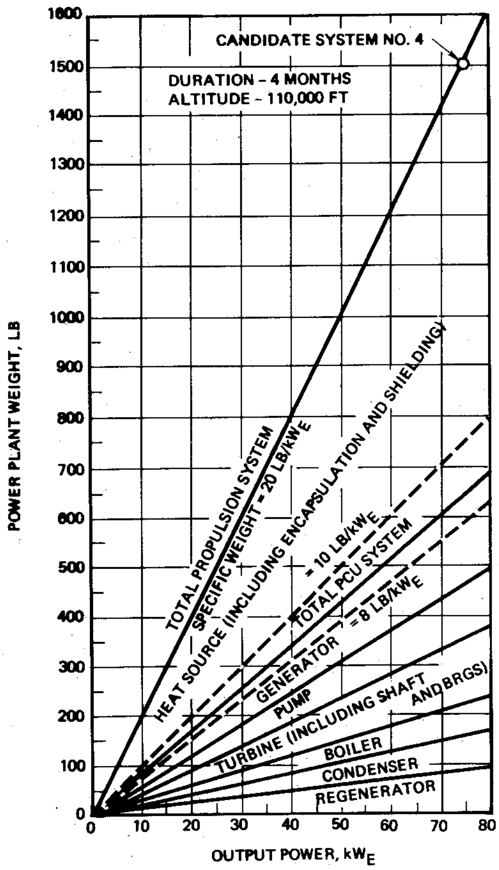

Fig. 9 Weight summary of Po^{210} isotope powered ORCEPS powerplant (candidate system 4).

Table 3 Candidate RPV propulsion system characteristics (1500 lb total allowable weight)

Candidate system	Propulsion system	Specific weight, lb/kWe	Specific fuel consumption, lb/hp-h	Output power, kWe
1	Solar array/secondary batteries	100	—	15
2	Propane/ORCEPS	9	0.40	13
3	Solar array/propane/ ORCEPS	33/9	0.40	13
4	Po^{210} isotope/ORCEPS	20	—	75
5	Pu^{238}	50	—	30
6	Liquid-metal (Nak) cooled U-ZrH reactor ORCEPS (4π shield)	100	—	15

Summary and Conclusions

The possibility of achieving long-duration operation with unmanned aircraft is a feasible option of many military applications. The propane-powered RPVs result in the shortest duration, lowest achievable altitude configurations. However, because these powerplants are based upon state-of-the-art hardware, they constitute the configurations with the lowest development risk. Also, they can be made applicable to a wide range of vehicle and payload weights and performances.

The isotope, reactor, and solar array/battery power sources offer the best potential for achieving longer-duration operation, albeit at the expense of increased development risk. Hence, they will probably be considered primarily where their use will considerably enhance the operational effectiveness of the mission.

Because high-altitude and reasonably long-mission operations appear to be the most desired characteristics for long-duration RPVs, the Po^{210} isotope/ORCEPS represents the candidate configuration that most closely approaches meeting these requirements. A weight summary of this system is shown in Fig. 9. Because it is possible to configure this system at power levels less than 75 kWe, this powerplant can be utilized for a wide range of long-duration unmanned aircraft carrying out a great variety of missions.

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