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SPECIAL PROBLEMS AND CAPABILITIES OF HIGH ALTITUDE LIGHTER THAN AIR VEHICLES†

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ABSTRACT: Powered LTA vehicles have historically been limited to operations at low altitudes. Conditions exist which may enable a remotely piloted unit to be operated at an altitude near 70,000 feet. Such systems will be launched like high altitude balloons, operate like non-rigid airships, and have mission capabilities comparable to a low altitude stationary satellite. The limited lift available and the stratospheric environment impose special requirements on power systems, hull materials and payloads. Potential nonmilitary uses of the vehicle include communications relay, environmental monitoring and ship traffic control.

INTRODUCTION

The High Altitude Super pressured Powered Aerostat (HASPA) Program in which we are now engaged, will design, build, and test fly an LTA vehicle. While looking much like a conventional airship in shape and size this vehicle, designed for an operational altitude of 70,000 feet, must be unlike its low altitude counterpart in many ways. In this paper we are not as interested in describing the HASPA program as we are in initiating a discussion of the related technology with the LTA community. As a remotely piloted vehicle (RPV) embodying aspects of airships, balloons and space platforms, the HASPA development must ultimately include many diverse elements of technology.

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OPERATING ALTITUDE

The operating altitude of 70,000 feet is not purely a matter of choice. One of the dominant features of the atmosphere is the existence of a minimum wind velocity near that altitude. A typical example of this minimum is shown in Figure 1.

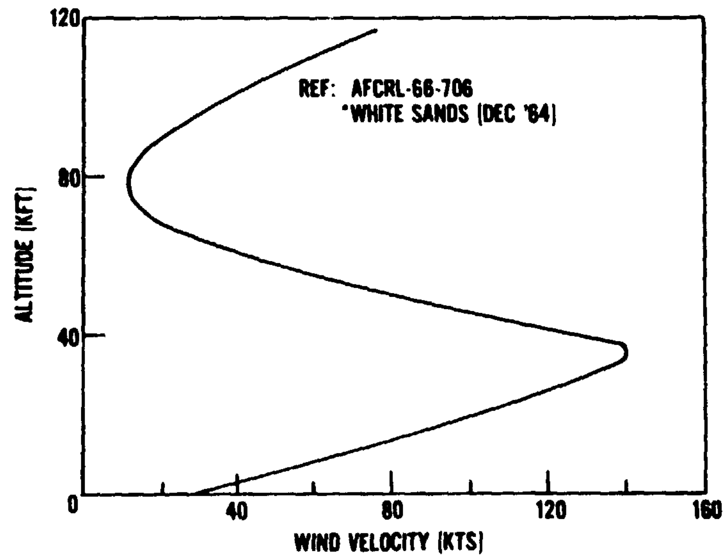

FIG. 1 TYPICAL WIND VELOCITY PROFILE

Clearly no other altitude offers a better design alternative. If, as a first approximation, drag (power consumption) and lift (power available) are both proportional to density while power consumption increases as the cube of velocity, then a minimum in the velocity/altitude curve represents an optimal point for operations. Thus we can say unequivocally that the next, and perhaps only, alternative to a conventional low altitude airship is one operating near 70,000 feet altitude. Future systems must carefully consider altitude controls to take advantage of favorable winds, even though this will exact a considerable penalty in weight and complexity.

It is purely fortuitous that the magnitude of the wind velocity remains low enough at most times so that it can be overcome by realistic system designs. Data on the distribution of wind velocities in the Northern Hemisphere at the 50 mb pressure level suggest that mean velocities in the midlatitude regions are typically 20 knots, with maximum velocities occasionally exceeding 30 knots. This condition generally persists from spring to autumn. Maximum velocities may exceed 40 knots at times for the more northerly latitudes in the winter and the equatorial regions in the summer.

Since the altitude of the minimum wind field varies as a function of latitude and season, the ability to control altitude or at least select the optimum point, would be highly desirable. The benefits to be obtained through altitude control can only be estimated from a reasonable knowledge of the temporal and spatial distribution of the high altitude wind field. Indeed, such information, which is presently very limited, is vital to the success of the entire concept.

By virtue of its influence on the operational altitude the wind pattern also affects other system characteristics, particularly volume and mode of operation. At 70,000 feet altitude the lift capability of either helium or hydrogen gas is approximately 4 lb/Mcf (pounds per thousand cubic feet). The weight of the power system needed to overcome the winds, plus the weight of controls and payload, and the vehicle weight itself combine to establish a minimum vehicle volume of approximately 1 MMcf (million cubic feet). Optimum system design requires hull materials with very high ratios of strength to specific gravity, power systems with high energy densities, and control systems and payloads using the lowest weight design approaches. It is evident that such systems must be unmanned, being unable to carry the weight of life support systems. Control systems cay profitably make use of RPV technology as previously indicated.

HULL DESIGN

The hull shape will be much like that of conventional airships, enabling designers to take advantage of well established formulas for weight distribution, balance, pattern configurations, and so forth. The required hull strength and the selection of a hull fabric will be determined by many factors.

Fabric Selection

Fabric selection will be determined by environmental conditions as well as by weight, strength, and other basic parameters of the material. The usual LTA problems of fluctuations in gas temperature and deterioration of fabrics as a result of exposure to sunlight are magnified at high altitudes where thermal coupling to the atmosphere is reduced and ultraviolet radiation is increased. The hull must retain its shape and volume over appreciable changes in temperature and pressure to maintain its controllability and altitude, and of course it must not leak. Thus the ideal hull fabric should be very strong, extremely light, insensitive to extremes of temperature, impervious to ultraviolet radiation, ozone and bombardment with charged particles, have limited elasticity and no creep, and be impenetrable to helium or hydrogen. For ease of manufacture the material should be easy to cut, seam, and seal, and be readily available and cheap. In addition it should be insensitive to folding and creasing, and have a storage life of several years under the poorest of conditions. How much of each of these properties is absolutely necessary (or available) remains to be determined.

Material Strength

Fabric strength requirements are determined by two parameters, supertemperature and hull diameter. The first of these is a complex function of the absorptivity and emissivity of the hull surfaces and the radiations emanating from the earth and the sun. Rough estimates of the temperature variation experienced by the fill gas indicate that it may be of the order of 80°F, resulting in a pressure variation (P) that is 20% of ambient or approximately 0.15 psi. From this figure and the anticipated hull diameter (D) of 60 to 70 feet, the required strength (S) of the fabric is

$$S = PD/2 = 54 \text{ to } 63 \text{ lb/in} \qquad (1)$$

Allowing for unequal stress loading, fabric imperfections and deterioration with time, and a reasonable safety factor increases the required strength to perhaps 150 lb/in. Analysis of other loads applied to the hull shows that they are far below this value. Effective control of the supertemperature, perhaps through application of thermal control techniques used in the space program, may allow appreciable reductions in hull strength and weight.

If we arbitrarily assume that 40% of the total system weight of 4000 pounds is hull material then the hull weight (W) alone will be 1600 pounds. Most of the fabrics considered as hull materials have densities (ρ) near 0.05 lb/in^3 and the total hull area (A) will be approximately 70,000 feet^2. Using these numbers we can estimate the tensile strength (T) required of the hull fabric. This is obtained from:

$$T = SA\rho/W = 47,250 \text{ psi} \qquad (2)$$

Fabrics of this strength, and greater, do exist. Whether or not they possess the other properties needed by the hull material is still under investigation. At the present time we are looking at the properties of many fabrics and materials. A Mylar/Kevlar combination appears particularly interesting.

Fabric Integrity and Durability

With mission durations expected to be of the order of months the hull fabric must retain its properties over a long period of time. Some stresses will be cyclic, but some will remain at all times. Hence the fabric must be able to withstand repeated stress loading and must have a high dead load strength. Resistence to creep must be unusually high. Inelastic elongation of even a few percent would cause the aerostat to become soft or limp at the low end of the temperature cycle. This would result in loss of shape and an inability to apply power or maneuver. Repeated exposure to solar radiation and extremes of temperature over the same extended time periods pose additional problems. This type of treatment is known to weaken and embrittle many materials.

The integrity required of the assembled hull is also very high. It must resist tearing or rupturing through the stresses and handling inherent in a high altitude balloon launch. Since the fabric will be much stronger than the usual balloon fabric this should be no problem. The permeability of materials like Mylar is more than adequate to limit gas losses by diffusion. Leakage is much more likely to be a problem. Relatively low leakage rates can become serious when extended over several months of time.

POWER REQUIREMENTS

Power requirements can be conveniently divided into three general categories, propulsion, payload operation, and control and telemetry. In general the greatest consumption will result from propulsion requirements. To estimate the power needed we will assume baseline system parameters as follows: Volume - 1 MMcf; Shape - Class "C" airship; Altitude - 70,000 feet; Speed 30 knots.

Propulsion Power

An appropriate expression for the drag, D, (of thrust, T) of a typical airship is,

$$T = D = \frac{1}{2}\rho C_D v^2 V^{2/3} \qquad (3)$$

where ρ is the atmospheric density (slugs/ft^3)

C_D is the drag coefficient

v is the flight velocity (ft/sec), and

V is the volume of the vehicle (ft^3).

Substituting the nominal system parameters Equation (3) leads to an estimated thrust requirement of

$$T = 0.1\ v^2 \text{ lbs} \qquad (4)$$

where v is expressed in knots, and a value of 0.05 is assigned to the drag coefficient. For a nominal speed of 30 knots the thrust requirement is only 90 pounds. This is an extremely small number when compared to the thrust requirements of the usual LTA vehicles. In the high altitude region thrust can be most efficiently provided by a larger low speed propeller, which may in turn be driven by an electric motor.

To produce this thrust level the power input to the propeller, P_i, reduced by the propeller efficiency ($E_\rho \cong 0.75$) must equal the product of thrust and forward velocity. Thus

$$P_i = \frac{0.167\ v^3}{E_\rho}\ \frac{\text{lb.ft}}{\text{sec}}\ . \qquad (5)$$

Additional efficiency factors must be included for the mechanical drive system ($E_d \cong 0.9$) and for the electric motor conversion of electrical power to mechanical power ($E_c \cong 0.8$). Introducing these and converting P_i to watts leads to the final expression for propulsive power:

$$P_i = \frac{0.22\ v^3}{E_\rho E_d E_c}\ \text{watts.} \qquad (6)$$

For the particular case under discussion this leads to a power requirement of 11 kW. The factor v^3 has been retained to emphasize its driving influence on the power requirement.

The primary uncertainties in the calculation of power requirements occur in the choice of the drag coefficient and the operating speed. A considerable body of data on drag was accumulated for airships at lower altitudes but the extrapolation to higher altitudes is uncertain because the Reynolds number moves into the transition region. Various estimates of the drag coefficient have ranged from 0.03 to 0.11. The uncertainty over the speed is due to the limited data on wind conditions.

Other Power Needs

Within the limits of the few hundreds of pounds of payload that the baseline system might carry, it is unlikely that payload power requirements will exceed the kilowatt level on a continuous basis. This would represent a small increase in the total power system capability required. Very efficient and sophisticated control and telemetry units have been developed and used for both high altitude balloon operations and for remotely piloted vehicles. The power consumption of such systems is typically a fraction of a kilowatt. This would also represent a small addition to the propulsion power requirements.

It is evident that power requirements will be largely determined by propulsion needs. Those needs will depend on unpredictable wind conditions and must therefore be considered as a continuous requirement for a long term system. By comparison to the 10 kW required for propulsion, the 1 kW required for payload and control functions is of lesser concern.

POWER SOURCES

Primary Power Sources

The term "primary" is used here to denote any system which uses a consumable fuel or non-renewable stored energy. Such systems will be limited by the small amount of fuel that can be carried aloft. We can readily make a rough estimate of what these limitations are. As a rough guideline we will assume average power requirements of 10 kW for electrical systems, to be provided out of a total weight of 1500 pounds, and 7.5 kW (10 shaft horsepower) for mechanical systems, to be provided out of a total fuel load of 1200 pounds.

Batteries - Some of the APOLLO space program primary batteries produced nearly 100 Wh/lb, which was the highest energy density available until very recently. At a power level of 10 kW, 1500 pounds of these batteries would last for 15 hours. Future battery developments promise as high as perhaps 300 Wh/lb which would provide power for 45 hours of flight. Thus even the most optimistic assumptions will result in inadequate mission durations to justify the system.

Fuel Consuming Engines - Liquid fueled, air-breathing engines may be difficult to operate efficiently at high altitudes, but we will ignore that point in our consideration. Whether one chooses a Wankel, a diesel or a turbine the basic fuel has an energy content of about 6000 Wh/lb. At an unrealistic 50 percent conversion efficiency this would be reduced to 3000 Wh/lb and the 1200 pounds of fuel would be exhausted in 20 days. For some applications this period may be adequate, if it can be provided.

Regenerative Power Sources

For this application we believe that it is possible to construct a regenerative system utilizing power from a solar array. An energy storage system, such as batteries would be used to provide power at night. An alternative approach, requiring substantially less weight, is a regenerative fuel cell.

The regenerative fuel cell system is composed of four basic components, as shown in Figure 2, and associated controls and plumbing. The system operates around a hydrogen/oxygen fuel cell which derives electrical energy from the conversion of those gaseous reactants into water. The water produced by the fuel cell reaction is pumped into an electrolysis chamber where the passage of an electrical current reconverts it to the gaseous state. Product gases are then held in high pressure storage until needed by the fuel cell. Electrical energy for operation of the electrolysis cell is obtained from a solar array distributed on the upper surface of the aerostat. Each of these major components has been developed and is available in some form today, though not optimized for the aerostat power application. We have attempted to determine the capabilities of existing hardware and project the results of anticipated modifications and improvements to estimate the performance of future systems.

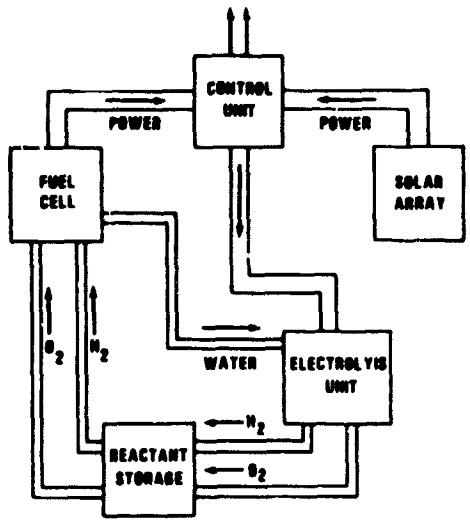

FIG. 2 REGENERATIVE FUEL CELL SYSTEM BLOCK DIAGRAM

Fuel Cell - The basic element of the power system is a hydrogen/oxygen fuel cell of the type used in space programs, which can meet very stringent requirements. The characteristics of a particular unit in which we are interested are as follows:

Average Power Output per Module	5 kW
Maximum Power Output per Module	10 kW
Specific Reactant Consumption	0.8 - 0.9 lb/kWh
Specific Weight at ave. output	25-30 lb/kW
Anticipated Cell Life	> 10,000 hrs.

Systems designed expressly for aerostat use should achieve a 10 kW output with a specific weight of about 15 lb/kW and a specific fuel consumption of 0.8 lb/kWh in the not too distant future. Significant advances beyond this point will be difficult since operating efficiency will be approaching realistic limits and weight reductions would result in more fragile and more costly components.

Solar Array - The FRUSA or Flexible Rolled-Up Solar Array[2] development indicated that it was possible to place solar cells on a flexible plastic sheet with imbedded interconnections and achieve excellent reliability with very lightweight panels. It was capable of providing a power level of 52 W/lb, and advanced array systems utilizing lightweight cells were expected to produce 70 W/lb. Utilizing the FRUSA design without the protective glass cover slide, which may be unnecessary for terrestrial applications, would result in a power density of nearly 80 W/lb.

Recent announcements of advances in solar array performance, through increased light conversion efficiency, indicate that the present 10 to 11 percent efficiency may be raised to 14 to 16 percent levels. Indeed there are some suggestions that the influx of new efforts and support in energy research may raise the efficiency to 20 percent over the next few years. In any event it is not unreasonable to expect that the specific weights of 12 to 15 lb/kW available with existing technology will be reduced to 7 to 8 lb/kW in the future.

While the specific weight of the solar array may be low it must be remembered that it will be the ultimate source of all power. Since power can be generated only during the daylight hours the size of the array will have to be approximately doubled to account for the power needed during night hours. The exact factor will depend on geographic location and time of year. Since all parts of the array cannot be oriented directly toward the sun at all times another factor of two must be included to account for the average sun angle. A minimal roll control system on the aerostat would provide this level of capability in sun alignment. Finally, the fuel cell/electrolysis cycle, water/H_2-O_2/water, is no more than 60 percent efficient. Thus, an additional expansion of the solar array must be made to account for this power loss. To generate power adequate for a 10 kW continuous level of consumption will require a total generating capacity of 53.4 kW. This level can be reduced somewhat by improving the fuel cell efficiency.

Electrolysis Unit - An electrolysis unit, with an efficiency of better than 90 percent, has been developed for use in space. It is expected that the specific weight may be brought as low as 3 lb/kW. Operation is inherently stable, is unaffected by pressure, produces pure reactants, and requires only modest controls. Reliability and life expectancy are high.

Reactant Storage - To supply the fuel cell with reactant to produce 10 kW for 12 hours at a specific fuel consumption of 0.8 lb/kWh will require nearly 100 pounds of reactant, or roughly 11 pounds of H_2 and 88 pounds of O_2. At atmospheric pressure this would represent 2000 cubic feet of H_2 and 1000 cubic feet of O_2. The volume can be reduced by increasing the storage pressure. Some recent developments in the fabrication of filament wound pressure vessels have greatly reduced the weight required for gas storage. Test results indicate a storage specific weight requirement of about 0.025 lb/ft^3 atmosphere, or a specific weight of 7.5 lbs/kW. Making full use of the available strength of these new materials would reduce the specific weight for reactant storage to about 5 lbs/kW.

System Summary - Combining the specific weights just discussed and including reasonable allowances for power conditioning, cabling, and other components, leads to an estimate of 88 lbs/kW for a complete regenerative power system. The life of each major component is of the order of 10,000 hours, offering the possibility for mission durations in excess of a year. Within the 1500 pounds of power system weight a capacity of 17 kW could be provided. This would increase the nominal speed capability to 35 knots, and enhance the utility of the vehicle.

APPLICATIONS

In addition to such obvious military applications as surveillance and communications relay, such a vehicle may find many uses in the commercial and governmental spheres. By being able to maintain an essentially fixed position for periods of the order of months it may usefully serve as a monitoring platform with line of sight coverage to more than 400,000 square miles of surface area. Thus it could provide environmental monitoring over entire drainage basins, serve as an educational TV outlet for large areas, as a system for monitoring or directing waterborne traffic in large harbor complexes, or provide continuous monitoring of offshore oil fields. In addition to these tasks the platform would be well suited for high altitude meteorological research. Its ability to carry out observations on a continuous basis at a fixed point would provide a dimension not readily available at the present time.

SUMMARY

This slightly unconventional airship is still a concept, as are many of the other ideas we have discussed. Translating those concepts into a high altitude instrument platform is the real challenge.

The ability of such a platform to perform useful missions, practically and economically, will depend on technological advances expected in the near future. These are primarily in the areas of solar array weights and costs, improvements in materials, and weight reductions in sensors and electronic assemblies. With such improvements the high altitude aerostat may become a valuable part of many programs in the 1980's.

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