Initial Sizing and Sensitivity Analyses of Stratospheric Airships for Psuedolite Based Precision Navigation System

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This paper presents the key results of a study on development of Stratospheric Airships as a HALEP (high altitude long endurance platform) for providing navigation and guidance for an airborne system, using the concept of inverted GPS. Details of an existing methodology for carrying out the initial sizing of an airship powered by electrical motors using solar regenerative fuel cells to meet a set of some user specified operational requirements are presented. The methodology can also be used for carrying out a specification tradeoff and sensitivity analyses. The methodology calculates the Envelope Volume required, and dimensions of a Stratospheric airship, given the parameters such as Operating altitude, Speed, Payload, available Irradiance, Solar Cell Efficiency, Atmospheric Conditions, and Propulsion system efficiency. A detailed methodology for estimation of the weight breakdown of the various groups/subgroups of an airship platform was developed, and validated against some published results from a previous study. The methodology was utilized to obtain the sensitivity of the payload capacity and envelope volume with some critical parameters such as operating altitude, ambient temperature, ambient wind speed, Helium purity level, engine power, envelope length to diameter ratio, charging discharging time. The results indicate that the ambient wind conditions greatly influence the size of the powerplant and hence the vehicle size. Usage of Ni-Cd onboard batteries was seen to result in exceptionally high system weight. Therefore a solar RFC based electrical propulsion system turns out to be an appropriate choice for the powerplant configuration.

I. Introduction

Research agencies in many developed countries like USA, UK, Europe, Japan and Korea have launched programs for design and development of unmanned stratospheric airships for various communication related applications viz., environmental monitoring, communication and broadcasting. Epley[1] has summarised the technological developments in USA on high altitude long endurance platforms, and provided an overview of the stratospheric airship programs carried out in the USA in the past. Kueke et al.[2] have provided the details and the proposed roadmap for the European stratospheric airship program. Advanced technologies and novel configurations and features are being incorporated on stratospheric airships to achieve outstanding performance. Some of these features include non-rigid or semi-rigid structure with aerodynamic shaping; on-board power for station-keeping as well as for the payload from lightweight solar cells during the day and regenerative fuel cells at night; coupling of vector-able propellers for cruise/lift augmentation; bow and stern thrusters for low speed manoeuvrability; Fly-By-Wire, fibre optic control paths and automatic control systems. Technology developments in composite materials have resulted in fabrics with enhanced strength-to-weight ratio, and UV resistance and permeability to Helium, leading to improvements in performance and safety. Novel configurations include a twin hull hybrid vehicle that uses both buoyant and aerodynamic lift and air cushion landing gear.

GPS based navigation systems for navigation and guidance of strategic vehicles suffer from three potential risks related to the integrity, availability and accuracy of the signals. Integrity risks are involved due to intentional and unintentional in-band interferences to GPS signals deceptive jamming can misguide a GPS receiver to give incorrect navigation solutions. Availability risks are due to full control on the GPS system by US DOD, who can selectively degrade/deny the GPS signals to any user agency in a critical situation. The third risk is the accuracy risk, which

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comes from the authorization to use only the C/A code, which can give an accuracy of only a few meters, after removal of selective availability. In order to maintain the integrity, availability and precision of a GPS based guidance system under jamming environment, there is a need to develop a navigation system which will augment the functionality of existing GPS based navigation system in normal situations, and in critical situations, it should be able to give precise navigation solution independent of NAVSTAR/GPS satellites.

The transmitters of GPS-like signals, which are called Psuedolites, or "pseudo-satellites", have been widely investigated as additional ranging sources to enhance the performance of GPS. Ground-based GPS augmentation systems using Psuedolites have been investigated for several applications such as vehicle navigation in downtown urban canyons, positioning in deep open-cut pits and mines, attitude determination, and precision landing of aircraft. Tsuijii et al.[4] have proposed that stratospheric airships can act as a high altitude long endurance platforms for mounting pseudo satellites for the precise guidance of the airborne vehicles, with a view to over the three potential risks in using GPS based system, as outlined above. Fig. 1 illustrates the basic outline of such a system.

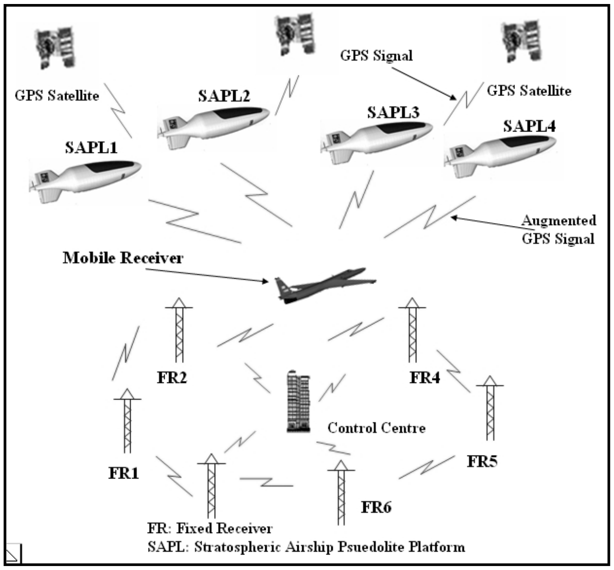

Figure 1. Precision navigation system using Psuedolites mounted on Stratospheric Airships

If Psuedolites were mounted on such HAPs, their GPS-like signals would be stable augmentations that would improve the accuracy, availability, and integrity of GPS-based positioning systems. Such a concept for navigation and positioning service based on Psuedolite installed on stratospheric airship platform possess several attractive features. Since they are based on proven GPS technology, their reliability is high. They can either augment the GPS based system, or provide local area positioning in absence of GPS signal. The receivers could be customized, and under the full control of the user, since the position of platform can be shifted as per requirement.

Tsujii et al.[5] have also highlighted the technological challenges that will arise during the development of Psuedolites mounted on stratospheric airships. Although many applications using Pseudolites have been proposed, an operational system has not been established due to pseudolite specific so called ‘near-far’ problem, multipath, and time synchronisation. But these problems are not so critical if the pseudolites are used in stratospheric airships. This is due to lower altitude of operation (17-22 km) and the distance between the Pesudolite and the user is in the range of 20-100 km leading to the minimum dynamic range as compared to the stationary Pseudolites. This also leads to the lesser multipath of Pseudolite signals due to higher elevation angle. The results of an experimental study by Tsujii et al.[5] indicated that one of the most significant technological challenges for such a service is the precise positioning of the transmitting antenna on the platform.

II. Description of the sizing methodology

A methodology to arrive at baseline specifications of stratospheric airship platform was developed, and used to carry out sensitivity analysis. This methodology is broadly based on the procedure suggested by Rehmet[6,7].

The methodology is divided in two parts; the first deals with the shape and material for the envelope, and the second with the propulsion system. These are cross-linked to get the proportionate variation with respect the drag; since drag is a function of envelope shape and size. This method does not include the parameters and equations that give mass breakdown. Therefore, this methodology can only be used to arrive at the initial sizing of the platform based on the given design parameters. Fig. 2 depicts the design flow that is used for the initial specification trade off.

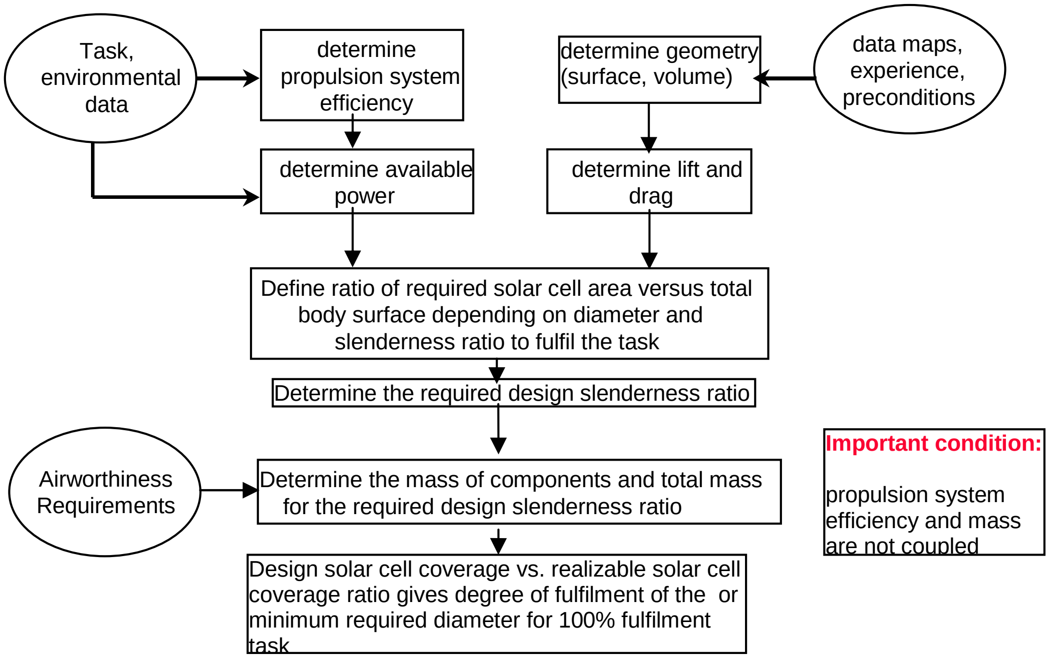

Figure 2. Initial sizing methodology flow[6,7]

A. Design calculation procedure:

The stepwise procedure followed for initial sizing of the stratospheric airship is summarized below. First, the atmospheric data related to the stratosphere viz. density, pressure, and temperature, kinematic viscosity is estimated, using standard formulae listed by Anderson[8]. Considering variation in solar irradiance and wind speed throughout the year; drag, lift and solar cell size for required onboard power are estimated, according to the procedure outlined by Rehmet[6,7]. The calculation is initiated by assuming envelope fineness ratio (i.e., ratio of the envelope length to its maximum diameter), length of the envelope and the percentage of ballonet volume. The propulsive power is assumed to be 5% greater than that required to hold the airship against the given wind speeds by increasing the required thrust. This additional thrust will also be useful in accelerating the airship.

It is assumed that on an average day the charging and discharging time will be 12 hours each. If a year long mission is planned, the critical day will be during winter when the discharging time will exceed the charging time by an amount of 13-15 hours. The propulsion system power consumption is assumed constant over the whole day. The available solar energy is directly fed into the engine to minimize transformation losses. The difference between maximum generator output and engine input defines the maximum power that the storage system must be able to cope with. Since no data was available on the distribution of the efficiency of the energy storage system depending on the size and power, the simplification considered by Rehmet[7] shown in Fig. 3 was assumed. Knowing the mission data (location, altitude, time frame) and some geometric data, the generator output can be calculated.

The solar cell coverage ratio is a parameter that gives an idea of how much area of the total envelope surface area is covered to get the power almost 50 % more than the required. This signifies the total surface loading due to the solar cells and whether the top surface area is available for the required size. This ratio is calculated in terms of required thrust, irradiance, and the overall propulsion system efficiency. It also gives an indication of the bending moment experienced by the envelope due to surface loading, and thereby results in the requirement of additional internal pressure.

It was assumed that one-fourth of the surface is exposed to the solar irradiation. This depends on flight path and seems to be optimistic if the wind is coming from the north or south. Therefore, about 50 % more solar cells than the calculated are required (installed on both sides of the airship). Thus knowing solar cell coverage ratio and the envelope surface area, the required solar cell area can be calculated.

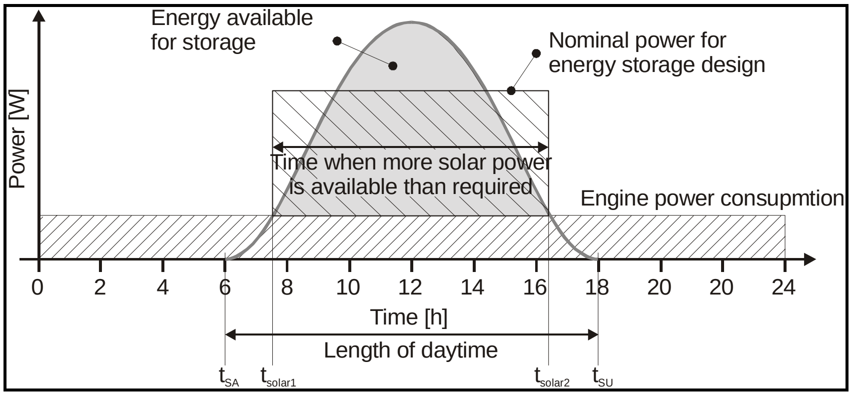

Figure 3. Energy Storage Power Diagram[3]

To define the weight of the envelope, the barrel formula outlined by Rehmet[6] in terms of the maximum internal pressure and maximum envelope diameter is applied. A factor of safety of six is chosen for rough estimation of the envelope weight, including the provisions for UV protection layers and gas leak proof layers. Further, an assumption is made for the evaluation of the structural weight that the empennage mass is equal to envelope mass. The total envelope mass is calculated by adding 20% margin for ballonets, all other miscellaneous mass is considered to be equal to zero for initial sizing. For long discharging times, the characteristics of regenerative fuel cell system, such as the one described in Fig. 4 by Rehmet[9] are better than that of batteries.

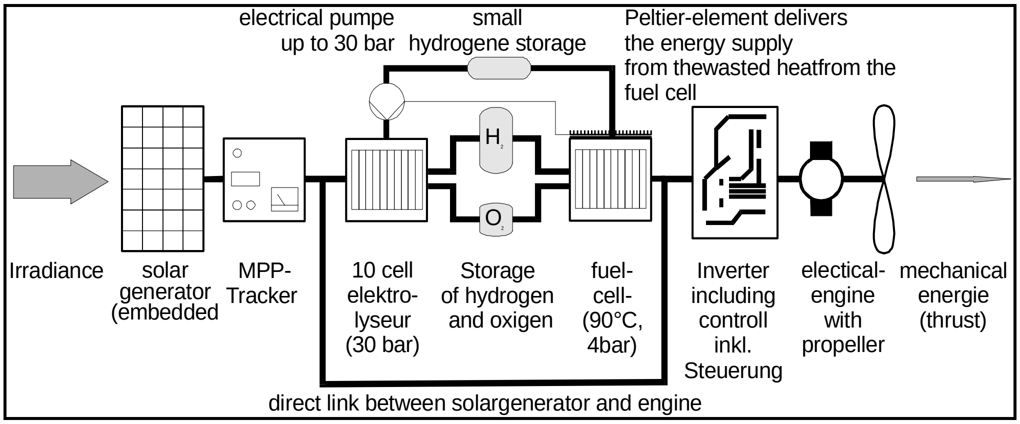

Figure 4. Energy flow of solar electric propulsion system using a regenerative fuel cell system as energy storage[9]

The mechanism of energy transfer is such that the solar irradiance is collected by photovoltaic cells and transformed into electrical energy. The maximum-power-point-tracker adjusts the amount of energy taken from the solar generator in such a way, that the maximum power is delivered. This power is either directly consumed by the engine or used to charge the energy storage system. One major subject is the development of the energy storage system. If the energy content of Nickel-Cadmium-Batteries is compared with that of fuel, a waste difference is found in the mass since Ni-Cd batteries have a specific mass of more than 20 kg/kWh and fuel has only 0.086 kg/kWh. Nevertheless, electrical propulsion systems can make sense, if the efficiency of all components is optimised, since such a system is the only solution for long duration operations.

To describe the solar powered propulsion system, various efficiencies, percentage losses in energy transmission such as Solar cells efficiency (including influence of temperature), propeller efficiency, electrical losses, total propulsion efficiency are required. Further, specific masses of Propulsion System in terms of mass of Engine, Engine Control and eventually required gearings, and mass of Energy Storage Systems, Control & Guidance System are taken from Rehmet[6,7]. Using the above information, the mass breakdown for Propulsion, Solar Generator, Energy Storage, Wiring and thus the total propulsion systems is worked out.

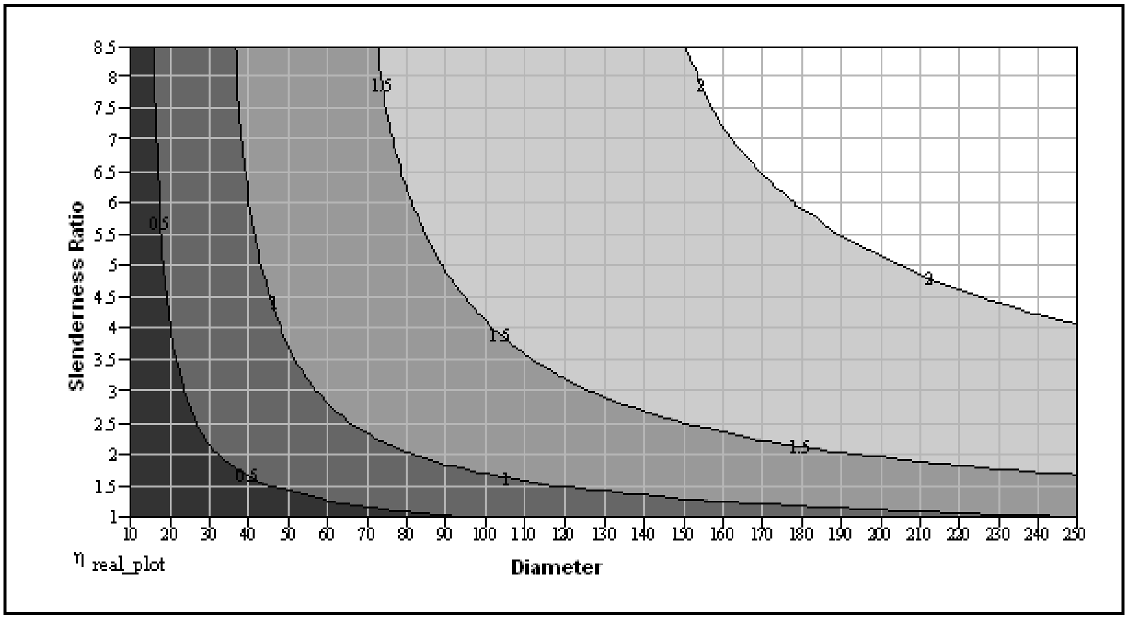

Figure 5. Solution surface for a given set of design parameters and a variation of diameter and slenderness ratios[7]

B. Concept of Degree of Fulfilment:

For a fixed Solar Cell Coverage Ratio, different feasible combination of fineness ratio and diameter exist, keeping all other driving parameters constant, as shown in Fig. 5. The ratio of Power available by means of the solar cell area to the Power required driving the propeller and the onboard instruments can be found out which is called as "Degree of Fulfilment of the task". This is evaluated because of existence of a minimum required body fineness ratio, below which the propulsion system cannot deliver sufficient thrust to reach the desired speed. The design body fineness ratio is that at which thrust exceeds drag.

III. Results

A. Validation of the methodology

The methodology for sizing of stratospheric airship described in the previous section was validated against the results quoted by Rehmet[6,7], for a payload mass of 1000 kg, assuming power consumption by payload as 10 kW. The envelope slenderness ratio was chosen to be 7.19, since it represented 100% degree of fulfillment. The results are presented in Table 1, and good comparison is seen for most parameters, except the solar cell surface area and the total propulsion system power required.

B. Results for the baseline case

Table 2 lists some key input parameters and the fudge factors for the baseline case. The envelope slenderness ratio was chosen as 7.64, since it resulted in a degree of fulfillment of 100% for similar payload and operating requirements listed in Ref 7. The fudge factors for certain parameters were decided based on the results of the validation reported in Table 1. Key output parameters and the mass breakdown for this case are provided in Table 3. These results are for the case with Solar Regenerative Fuel Cells as the energy storage system.

Table 2: Design parameters & Fudge Factors for baseline case

No.	Parameter	Unit	Value
1.	Payload mass	[kg]	50
2.	Power consumption by payload	[kW]	1
3.	Floating Altitude	[m]	20000
4.	Mission Speed	[m/s]	25
5.	Solar Cell Efficiency	[%]	20
6.	Slenderness ratio [l/d]	[-]	7.64
7.	Average Irradiance	[W/m^2]	480
8.	Discharging time	[Hours]	12
9.	Design Internal Pressure in Envelope	[N/m^2]	300
10.	Off standard Temperature	[K]	+20
11.	Helium Purity	[%]	99.999
12.	Mass factor for Fuel Tanks	[-]	0.10
13.	Technology factor for Electric Propulsion	[-]	0.80
14.	Technology factor for Energy Storage	[-]	0.50
15.	Energy Density of Regenerative Fuel Cells	[W.h/kg]	429
	Fudge Factors		
16.	Fudge Factor for Propulsion System Mass	[-]	1.02
17.	Fudge Factor for Thrust	[-]	1.06
18.	Fudge Factor for Energy Storage Mass	[-]	1.06
19.	Fudge Factor for Elec. Propulsion Mass	[-]	1.06
20.	Fudge Factor for Solar Cell Area	[-]	1.66

Table 3: Key output parameters and mass breakdown for baseline case

Sr.No.	Parameter	Unit	Value
	Key Output Parameters		
1.	Envelope Volume	[m^3]	129279
2.	Envelope Surface Area	[m^2]	19632
3.	Envelope Length	[m]	240.40
4.	Envelope max. Diameter	[m]	31.46
5.	Net Disposable Lift	[kg]	9653.23
6.	Surface Area for Solar Cells	[m^2]	1428.50
7.	Thrust Required	[N]	2473.3
8.	Power Required	[kW]	84.22
	Mass Breakdown		
9.	Electric Propulsion	[kg]	98.30
10.	Solar Generator	[kg]	882.60
11.	Energy Storage System	[kg]	1142.22
12.	Wiring and Control	[kg]	62.47
13.	Propulsion System	[kg]	2226.87
14.	Total Structure	[kg]	7376.35
15.	All up mass (without payload)	[kg]	9603.22

It may be noted that the value of solar irradiance taken is based on the graph of global irradiance throughout the year as given by Rehmet[9]. This value for Indian region was found to be 480 W/m^2 during summer season over the cities or locations which come above 280 degrees latitude. However, for the region below this range of latitude, the irradiance value found to be 450 W/m^2.

At ISA sea level conditions, Helium has the lifting force of 10.2 N/m^3, whereas for Hydrogen this number is 11.2, i.e. around 9.8 % more. But, even though, Hydrogen has the lowest density and therefore the highest lifting force, it is also highly inflammable. As far as the cost of these gases by volume is concerned, Helium costs almost 12-14 times higher than the cost of Hydrogen in India. However, to realize the use of Hydrogen, technology which ensures safe use of this gas is required to be developed.

IV. Sensitivity Analyses

Sensitivity of some important design parameters and operating conditions was studied for two baseline cases, viz., payload of 50 kg and 1000 kg with onboard power consumption of 1 kW and 10 kW respectively; for an operating altitude of 20 km and Helium as a lifting gas. Some results with Hydrogen as a lifting gas were also obtained. These variations are graphically represented in the sub-sections that follow.

A. Variation in the degree of fulfilment for various l/d at constant diameter

The degree of fulfilment of the task gives the minimum required l/d ratio which will be required to put the solar cells over the envelope to generate the power sufficient enough to fulfil the onboard and power plant needs. Figures 6(a) and 6(b) shows the result for 50 kg and 1000 kg payload and 1 kW and 10 kW of onboard power requirement.

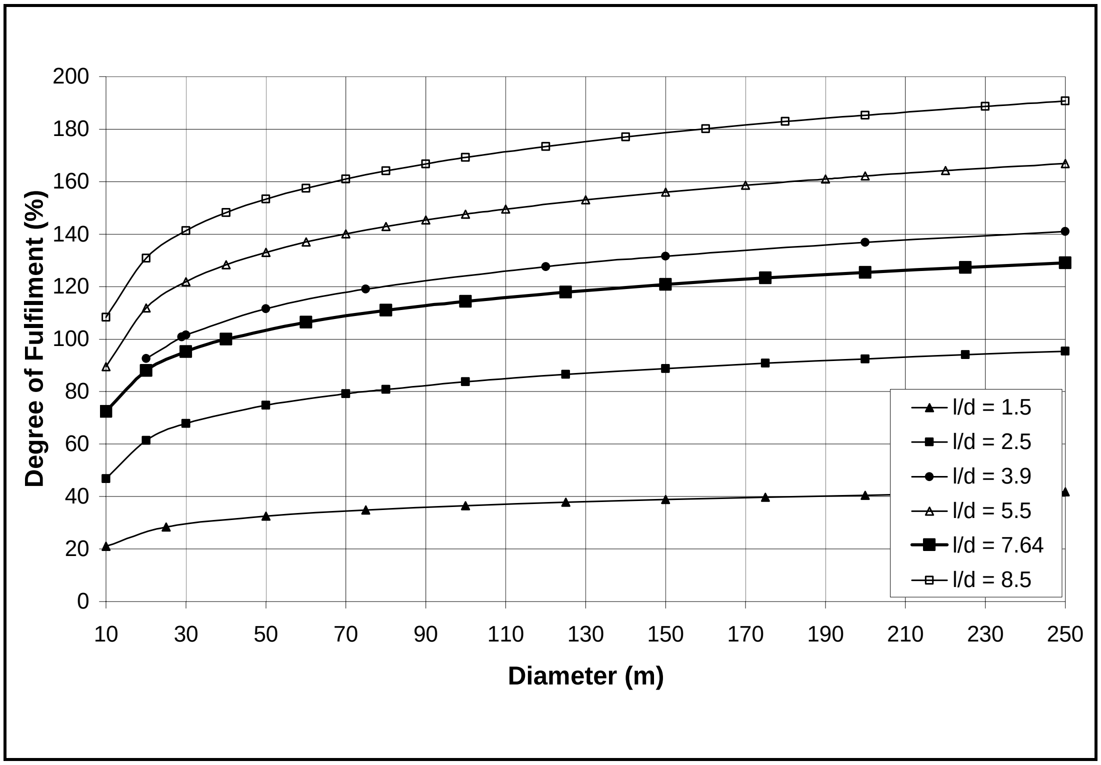

Figure 6(a). Degree of fulfillment of the task for 50 kg payload (Power = 1 kW)

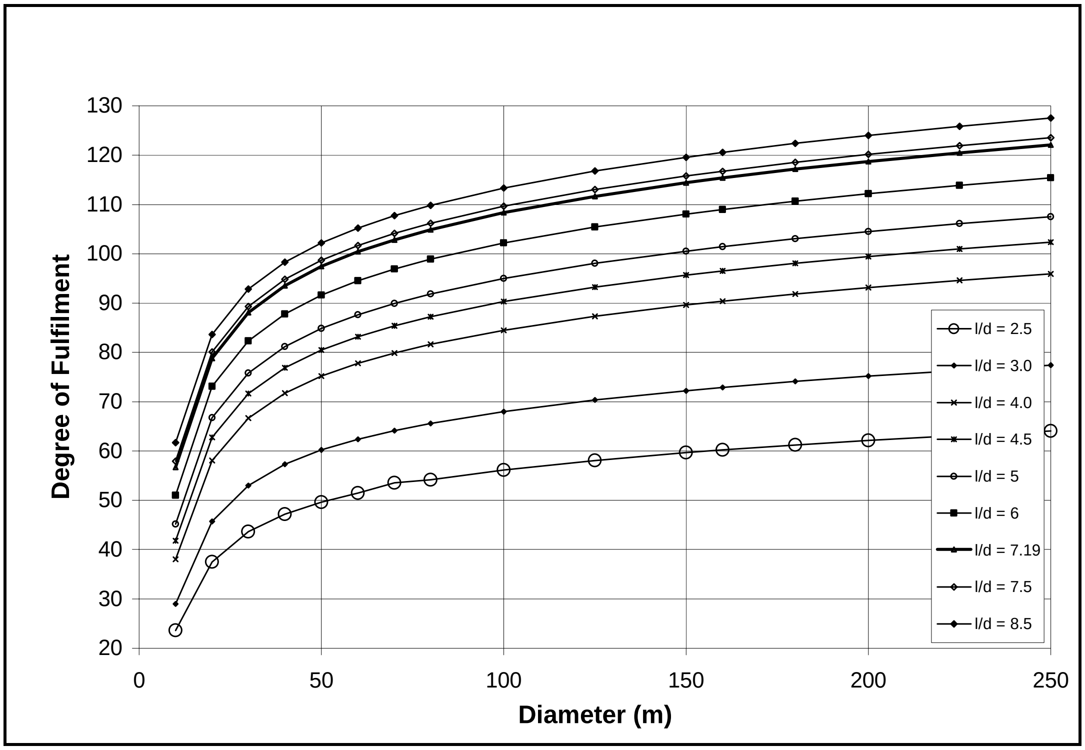

Figure 6(b). Degree of fulfillment of the task for 1000 kg payload (Power = 10 kW)

B. Effect of payload on volume

A variation of required envelope volume is shown in the Fig. 7 indicating almost a linear variation as the payload is increased for same operating altitude of 20 km.

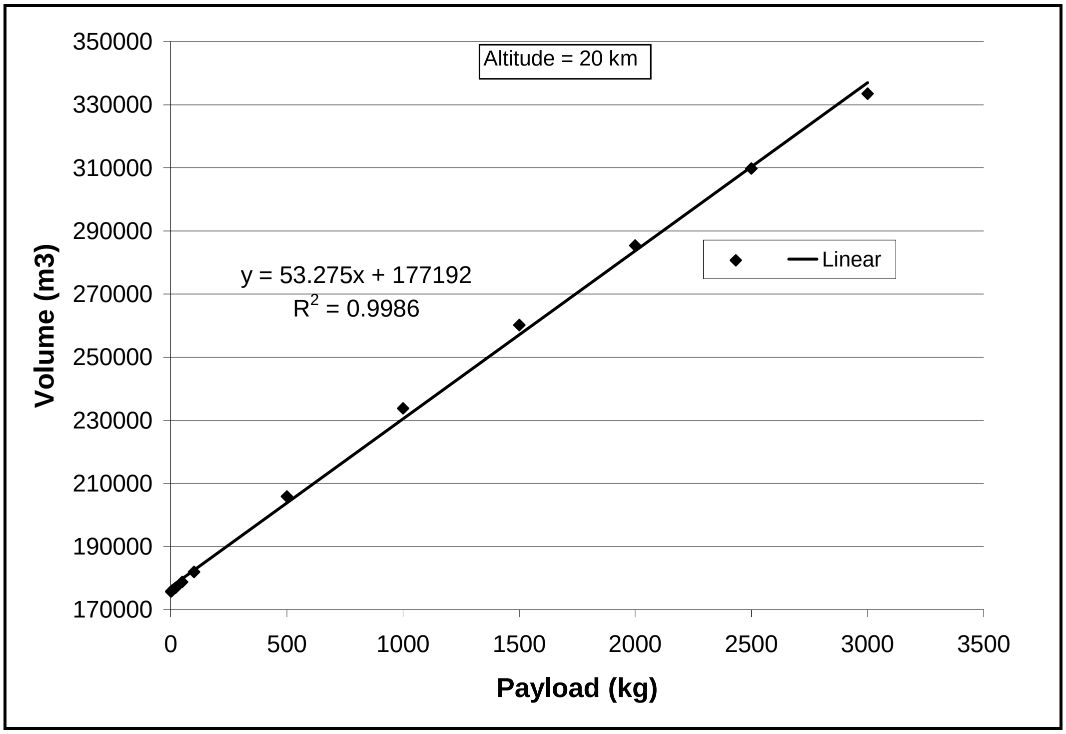

Figure 7: Effect of Payload on Required Envelope volume at same altitude

C. Drag and speed

An exponential increase in drag with forward speed was observed, as shown in Fig. 8.

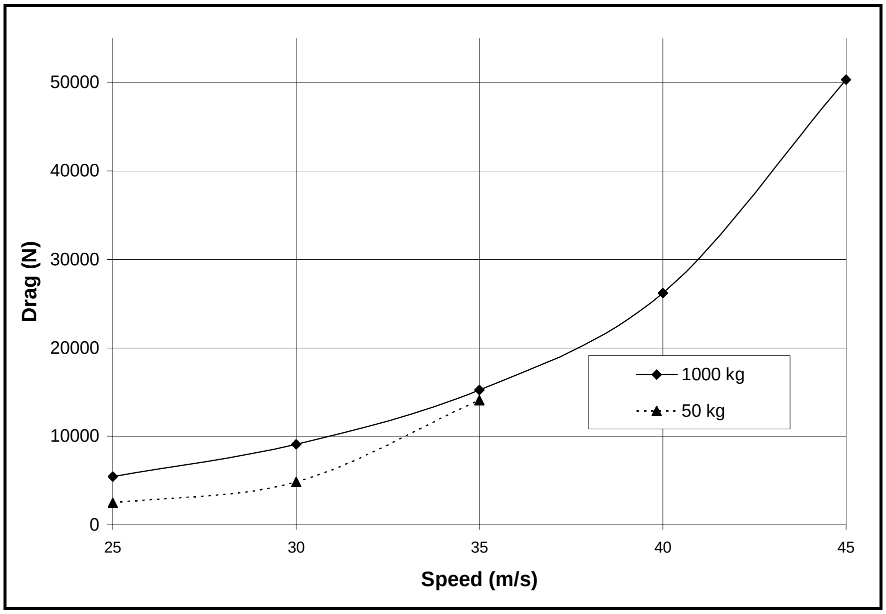

Figure 8. Effect of Payload on Required Envelope volume at same altitude

D. Volume and speed

The envelope volume also increases exponentially with wind speed, as can be seen in Figure 9(a) for 50 kg payload and in Figure 9(b) for 1 ton payload.

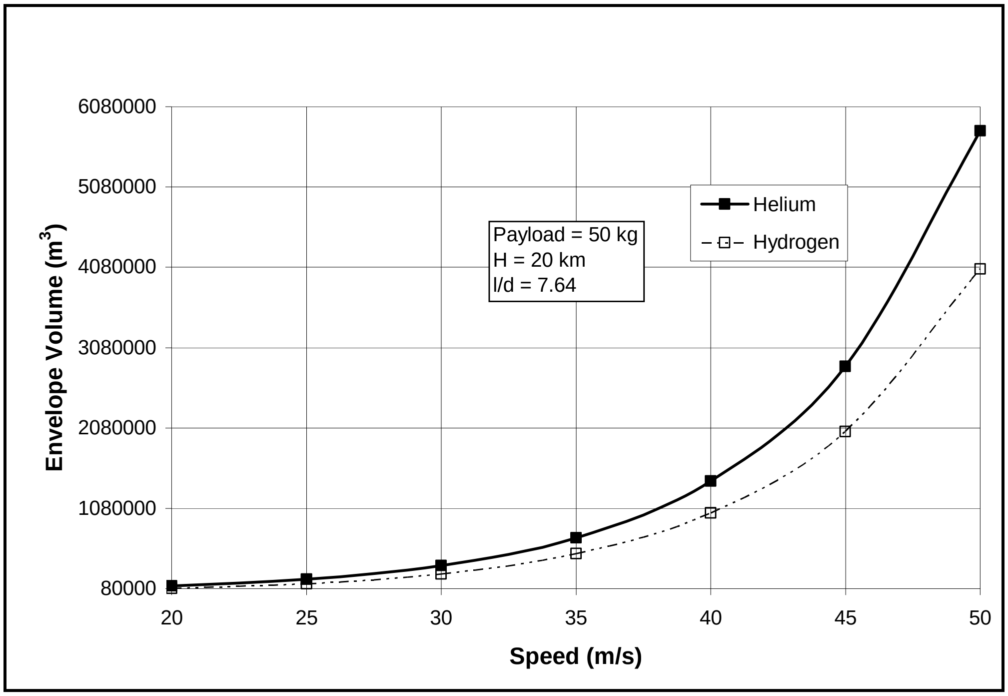

Figure 9(a). Required envelope volume for same fineness ratio and various design speeds

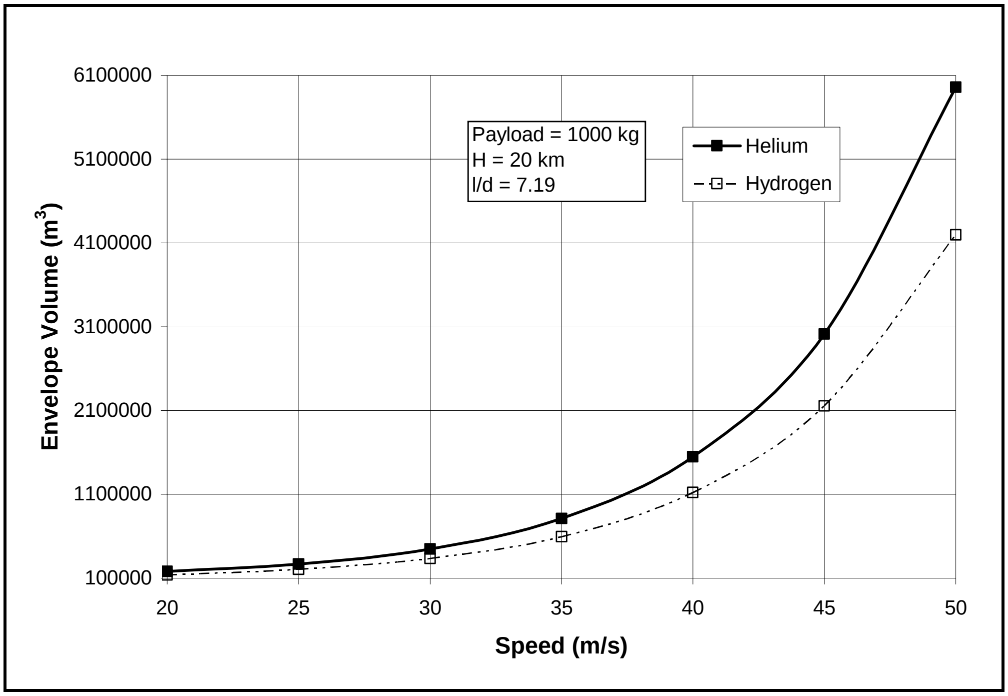

Figure 9(b). Required volume for same fineness ratio and various design speeds

E. Effect of SC efficiency on solar coverage ratio

Solar Cell efficiency largely affects "Surface Loading" on the envelope and thereby hull internal hull over pressure and so on. Figure 10 shows that the solar cell coverage ratio does not change much for the payload of 50 kg, but the variation for 1000 kg payload is quite substantial.

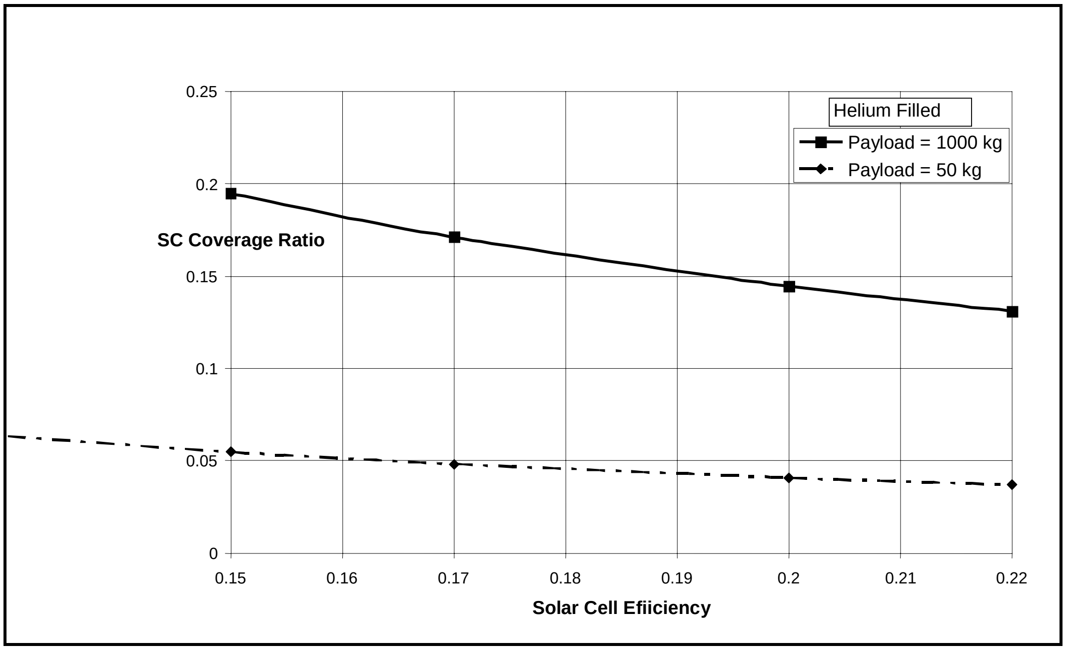

Figure 10. Variation in solar cell coverage ratio for 50 kg and 1000 kg and 20 km with solar cell efficiency

F. Battery v/s RFC as a Energy storage system

A variation in mass of energy storage by battery and RFC for 50 and 100 kg payloads is the shown Figure 11. Phenomenal increase in storage system mass for Ni-Cd battery is seen for1000 kg payload case, indicating that such a system is not suitable for high payloads.

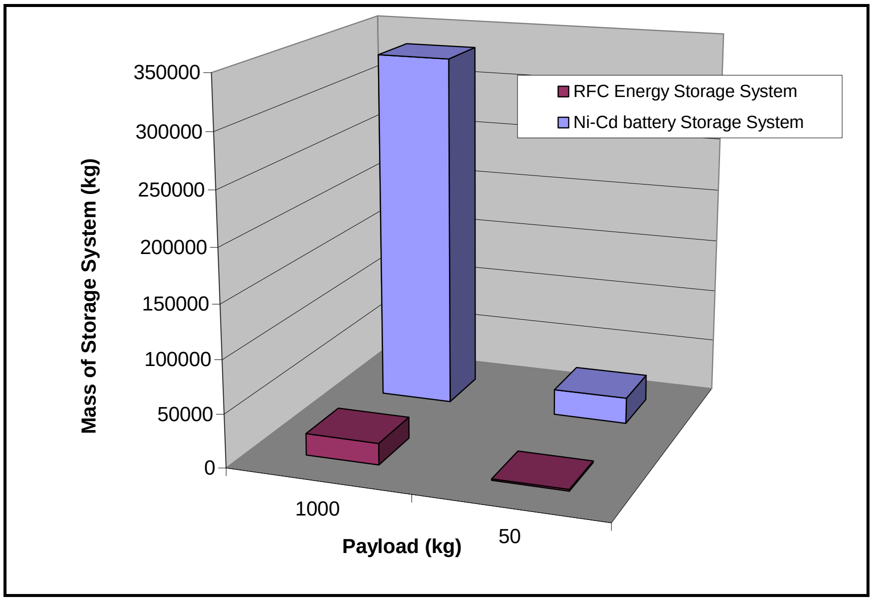

Figure 11. Battery storage against RFC storage for 50 kg and 12 hrs of charging time

G. Expected Solar Generator (SG) efficiency for given discharge time

Large changes in expected SG efficiency with increase in discharging time are observed, as shown in the Fig. 12.

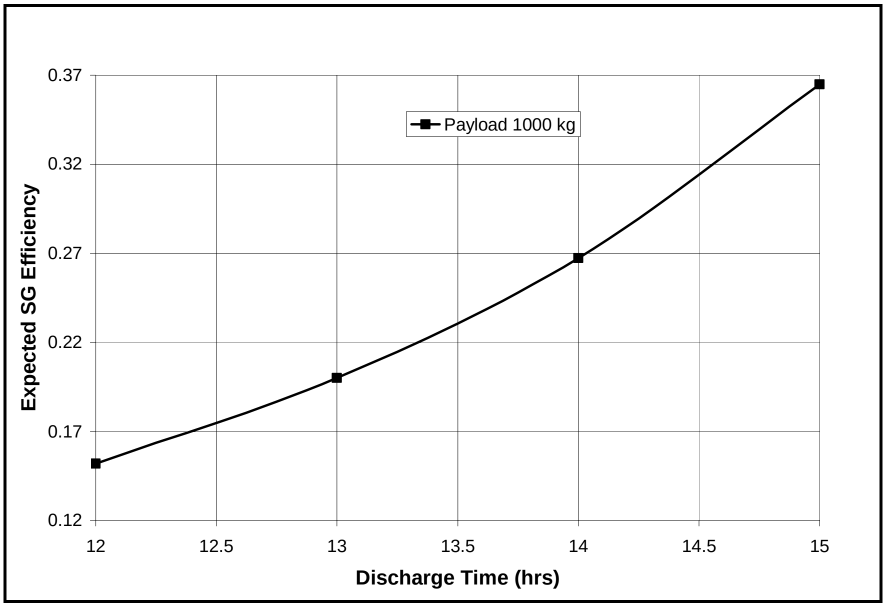

Figure 12. Expected solar Generator Efficiency for given discharging time

H. Solar Generator mass for given discharge time.

To store more energy in less charging time, Solar Generator size will be modified to respective discharge time. Here again, huge increase in solar generator mass result with increase in discharge time, as shown in Figure 13.

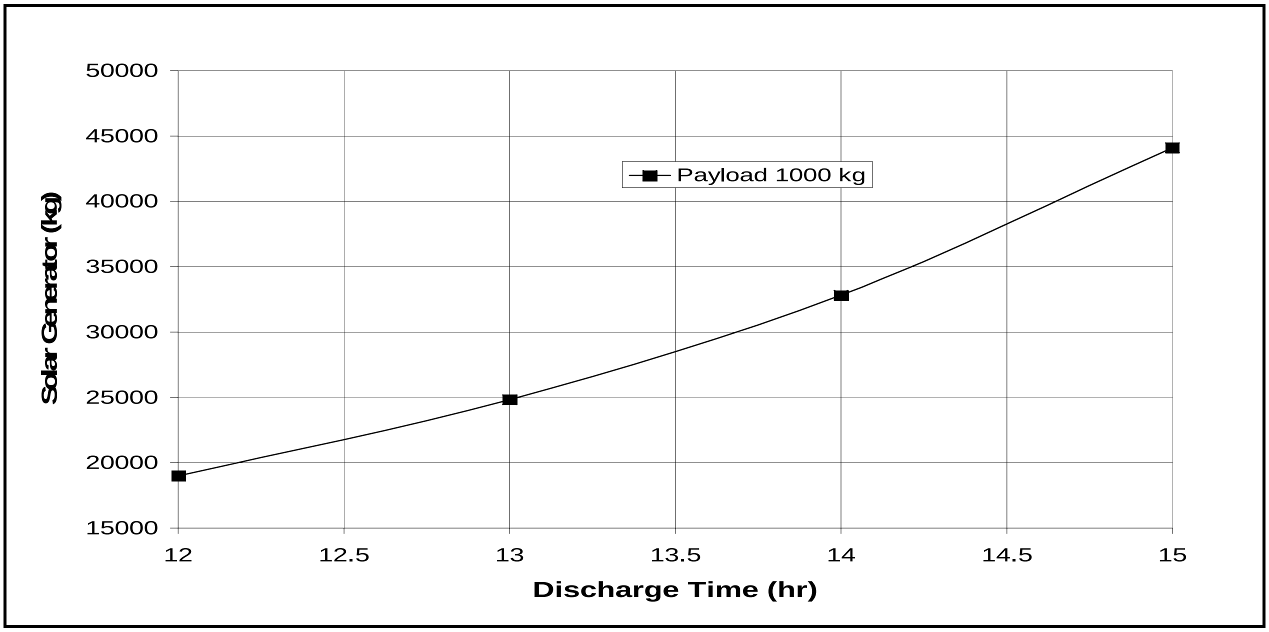

Figure 13. Effect of Discharge time on Solar Generator Mass for 1000 kg payload

I. Helium purity and loss in altitude

Decrease in Helium gas purity does not seem to affect the operating altitude by a huge amount, as can be seen in Figure 14.

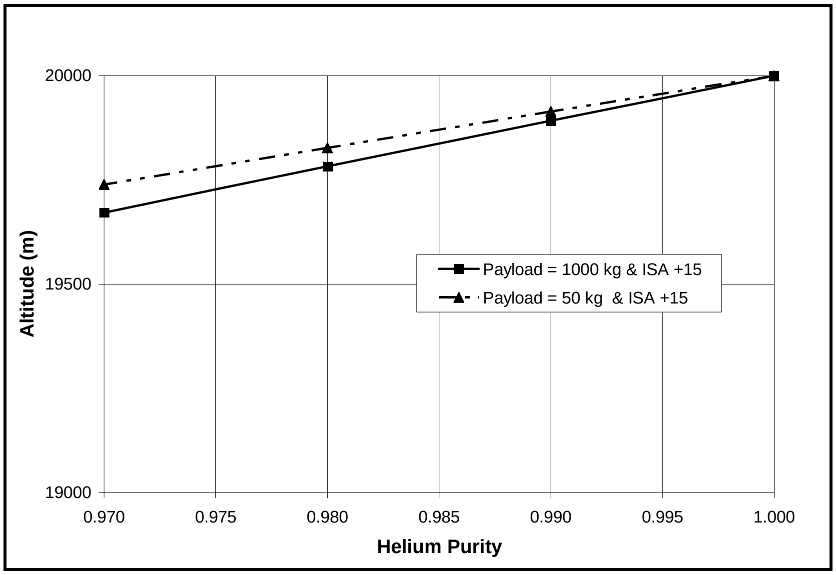

Figure 14. Loss in altitude due to reduction in Helium gas purity for 50 and 1000 kg.

J. Minimum volume at optimum altitude

Fig. 15(a) & 15(b) shows the effect of altitude on envelope volume for different ISA and for Hydrogen Gas worked out for 50 and 1000 kg payloads respectively. Lowest volume is expected at 20.5 km altitude for all cases.

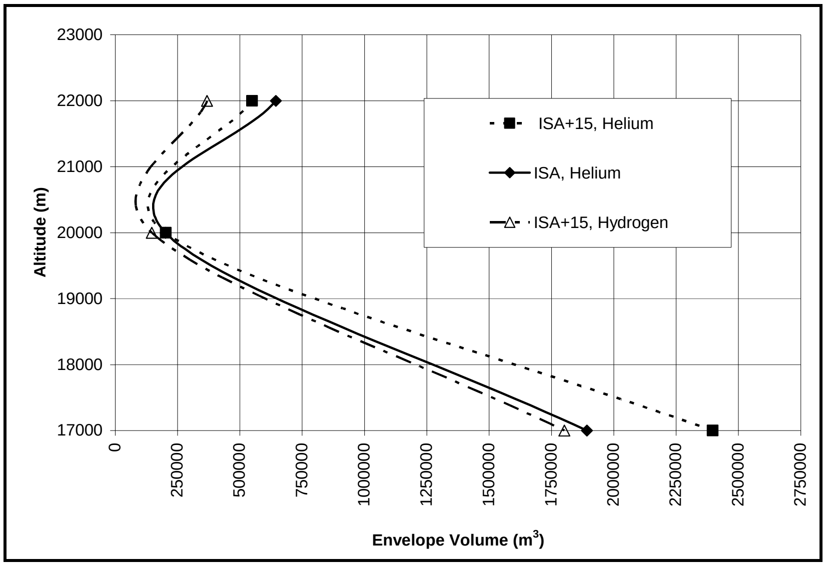

Figure 15 (a). Optimum altitude as indicated by the envelope volume for 50 kg payload.

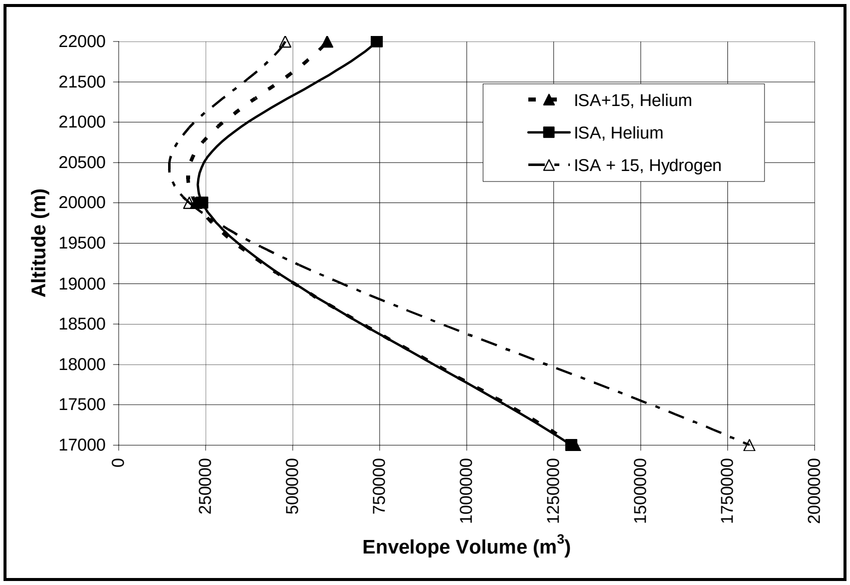

Figure 15 (b). Optimum altitude as indicated by the envelope volume for 1000 kg payload.

V. Key observations from results and sensitivity analyses

A summary of the important results and the sensitivity analyses are enumerated below.

1. The envelope volume increases linearly with the increase in payload. However, an increase in the payload does not lead to a proportionate increase in envelope volume for the same operating conditions. For instance, a 20-fold increase in payload (from 50 kg to 1000 kg) can be achieved by only a 12-fold increase in the envelope volume (from 129279 m^3 to 1546441 m^3).
2. The envelope drag was seen to increase exponentially with the ambient speed. This result in exponential increase in envelope volume required for station keeping with increase in the ambient speed, if the envelope fineness ratio is maintained. As the ambient speed is increased from 20 m/s to 50 m/s, the required envelope volume increases nearly 50 times for a payload of 50 kg. However, this increase is nearly 30 times, for a payload of 1000 kg.
3. Efficiency of solar cell strongly affects the extent of envelope surface area to be covered by solar cells. For the baseline case (payload = 50 kg), a 7% increase in solar cell efficiency (from a baseline value of 20%) leads to almost 50 % reduction in the solar cell coverage ratio (ratio of solar cell area to envelope surface area). For the case with payload of 1000 kg, the corresponding reduction is nearly 67%.
4. Usage of RFC leads to a phenomenal reduction in the energy storage system mass, compared to a Ni-Cd Battery. For instance, for 1000 kg case, the battery based energy storage is 17 times heavier than an equivalent RFC system. The results actually point out that it is infeasible to use battery storage system due to exceptionally high weight requirements.
5. The required solar generator efficiency increases rapidly with reduction in charging time. For instance, if the charging time is reduced from 12 hours to 9 hours (due to seasonal variations), the required solar cell efficiency increases from 16% to 37 % for a payload of 1000 kg. On the same lines, the mass of the solar generator system is seen to increase drastically with reduction in charging time.
6. Reduction in Helium purity level with the passage of time leads to a lowering of operating altitude. For instance, for the case with 1000 kg payload, reduction in Helium purity from 99.999% to 97% results in a loss of 330 m in operating altitude.
7. As the altitude of operation is increased, the loss in buoyancy results in lower lift, and hence for a given payload, the required envelope volume is increased. At lower altitudes, lift is higher; however, the increase in ambient wind leads to a larger (and heavier) power plant to meet the station-keeping requirement. For the given operating conditions, the minimum envelope volume for the baseline case was seen to occur at an operating altitude of 20 km.

VI. Conclusions

The methodology for initial sizing of stratospheric airships powered with solar electric propulsion is quite useful for carrying out the conceptual design studies to get an estimate of the size and weight of various components and sub-systems, and to study the “what-if’ scenarios. The results obtained indicate that size of the airship in proportion to the payload capacity is substantially larger than that of other alternatives to carry the same payload. A Regenerative Fuel Cell system offers a substantially light-weight alternative for onboard energy storage, compared to the Ni-Cd batteries. It can also be concluded that the charging time available strongly affects the size and weight of the solar generator system. Since parameters such as ambient wind speed and temperatures very strongly affect the sizing of the stratospheric platform, details of meteorological characteristics in the stratosphere at the desired area of operation of the platform should be investigated and analysed. Modeling and simulation of the entire system can help to arrive at the appropriate values of the key design drivers that have been identified through the sensitivity analysis. This will also help in a more accurate estimation of the operating requirements and finalization of the system specifications. Effect of degradation of the envelope material due to environmental factors can be modeled by assuming a rate of effusion of the LTA gas from the envelope. Further studies are underway to incorporate the effects of such issues in the methodology.

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