



# Evaluation of Long Duration Flight on Venus

*Anthony J. Colozza*  
*Analex Corporation, Brook Park, Ohio*

*Geoffrey A. Landis*  
*Glenn Research Center, Cleveland, Ohio*

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at 301-621-0134
- Telephone the NASA STI Help Desk at 301-621-0390
- Write to:  
NASA STI Help Desk  
NASA Center for AeroSpace Information  
7121 Standard Drive  
Hanover, MD 21076-1320



# Evaluation of Long Duration Flight on Venus

*Anthony J. Colozza*  
*Analex Corporation, Brook Park, Ohio*

*Geoffrey A. Landis*  
*Glenn Research Center, Cleveland, Ohio*

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

*Level of Review:* This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information  
7121 Standard Drive  
Hanover, MD 21076-1320

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161

Available electronically at <http://gltrs.grc.nasa.gov>

# Evaluation of Long Duration Flight on Venus

Anthony J. Colozza  
Analex Corporation  
Brook Park, Ohio 44142

Geoffrey A. Landis  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

## Abstract

An analysis was performed to evaluate the potential of utilizing either an airship or aircraft as a flight platform for long duration flight within the atmosphere of Venus. In order to achieve long-duration flight, the power system for the vehicle had to be capable of operating for extended periods of time. To accomplish these two types of power systems were considered, a solar energy-based power system utilizing a photovoltaic array as the main power source and a radioisotope heat source power system utilizing a Stirling engine as the heat conversion device. Both types of vehicles and power systems were analyzed to determine their flight altitude range. This analysis was performed for a station-keeping mission where the vehicle had to maintain a flight over a location on the ground. This requires the vehicle to be capable of flying faster than the wind speed at a particular altitude. An analysis was also performed to evaluate the altitude range and maximum duration for a vehicle that was not required to maintain station over a specified location. The results of the analysis show that each type of flight vehicle and power system was capable of flight within certain portions of Venus's atmosphere. The aircraft, both solar and radioisotope power proved to be the most versatile and provided the greatest range of coverage both for station-keeping and non-station-keeping missions.

## Introduction

Flight within the Venus atmosphere can provide a unique and valuable means for scientific investigation of the planet. Due to the harsh environmental conditions near the surface, few science probes or surface landers have been sent to Venus. Orbiting satellites, such as Magellan, and spacecraft flybys have been the main means of exploring the planet. However, because of the planet's thick atmosphere, a flight vehicle can be considered as another viable means of investigating the planet.

Flight vehicles can provide a unique perspective for the exploration of Venus. Ideally a flight vehicle would be capable of operating for long durations, on the order of months, within the atmosphere. This is considerably longer than what is achievable using atmospheric probes that would only have a lifetime of hours at best. In addition to long mission times, controlled flight within the atmosphere provides a means of investigating specific areas of the atmosphere. A flight vehicle operating within Venus's atmosphere can carry out a number of potential science missions. Some examples of these would be:

- The collection of atmospheric properties over a region of the atmosphere
- Direct sampling of the atmosphere
  - Provide information on atmospheric makeup
  - Look for trace biogenic gasses as indicators of life
- Magnetic field mapping over a region of the planet
- Visual imagery
- Communications and command relay for surface vehicles and landers

To perform the types of science exploration listed above, two types of power systems can be considered to enable long duration flight within the Venus atmosphere, a solar energy powered photovoltaic array system and a radioisotope-powered heat engine system. These power systems can be utilized in both the airships and aircraft vehicle platforms. To examine their feasibility, a detailed understanding of the planet's atmospheric conditions is necessary. Items such as solar intensity, wind speed, and atmospheric density and temperature as a function of altitude are necessary to assess whether controlled flight is possible for each type of vehicle with each power system.

The slow rotation rate of Venus, approximately 13.4 km/hr, presents a unique opportunity for a solar-powered flight. This slow rate means that an aircraft will remain within the sunlit side throughout the mission, thereby eliminating the need for energy storage for nighttime operation.

Although the atmosphere on Venus is thick, providing significant lift for a flight vehicle, the high wind speeds, especially towards the upper levels of the atmosphere, are a major obstacle. These high average wind speeds mean that significant power will be required for the aircraft to maintain station over a specific location on the surface. So for an aircraft to be feasible for a station-keeping mission on Venus, it must be capable of producing enough thrust to overcome the wind speeds and generate sufficient lift to maintain flight.

## Environmental Conditions

Venus is the second planet from the sun and has a number of unique characteristics that makes its environment both interesting and challenging for flight. The basic physical and orbital properties of Venus are given in table 1. Venus is very similar in size to Earth. However this is where the similarities end. The environmental conditions on Venus are very unique and unlike those on any other known planet or moon. Venus is a place of environmental extremes. Near the surface, the atmospheric temperature is very hot (over 700 K) and there is very little useable sunlight due to the extensive cloud cover that covers the whole planet. The cloud cover extends from approximately 45 km above the surface to approximately 64 km above the surface. At the top of the cloud layer, the atmospheric pressure is around 0.1 bar. Within this altitude range, the atmospheric temperatures are between 80 to  $-35$  °C respectively. The top of the cloud layer corresponds to a pressure altitude of 16 km (52,500 ft) on Earth. Although high, this altitude is well within the range of modern aircraft and flight aerodynamics within this regime are well understood (ref. 2). A diagram of the Venus atmosphere is shown in figure 1.

TABLE 1.—PHYSICAL AND ORBITAL PROPERTIES OF VENUS (REF. 1)

Property	Value
Maximum inclination of equator to orbit ( $\delta_{\max}$ )	3.39°
Orbital eccentricity ( $\epsilon$ )	0.0067
Mean radius of orbit ( $r_m$ )	$10B \times 10^6$
Day period	243 (Earth days)
Solar radiation intensity	Mean: 2613.9 W/m <sup>2</sup> Parihelion: 2649 W/m <sup>2</sup> Apehelion: 2579 W/m <sup>2</sup>
Albedo	0.65
Gravitational constant (g)	8.87 m/s <sup>2</sup>
Sidereal year	224 (Earth days)
Surface temperature	737 K
Diameter	12,104 km

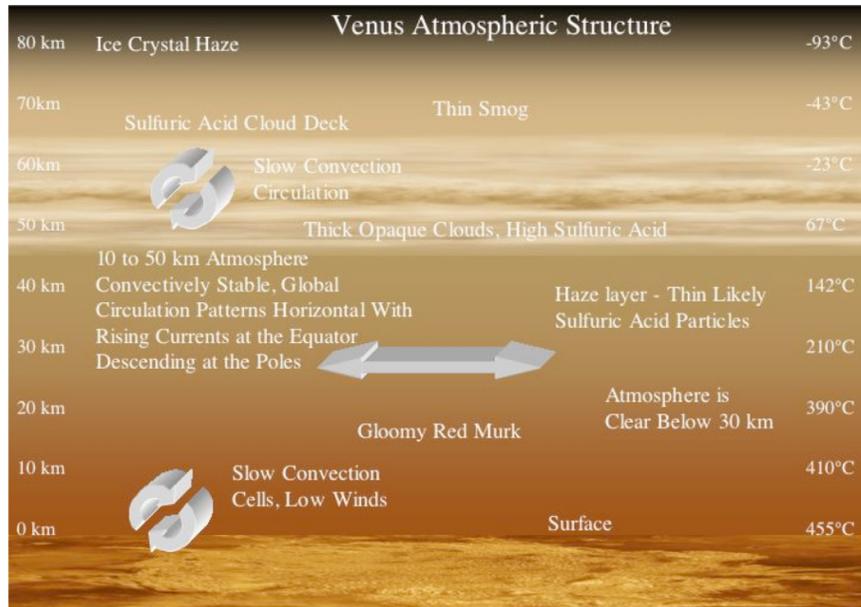


Figure 1.—Venus atmospheric structure.

Because of the thick atmosphere, the pressure and density throughout most of the atmosphere is much greater than that on Earth. The atmospheric pressure and density we experience near the surface of Earth occurs at an altitude of just over 50 km on Venus. For a flight vehicle, this means that flying at 50 km on Venus is similar aerodynamically to flying near the surface on Earth.

Above the cloud layer there is an abundant amount of solar energy. The solar flux at the orbit of Venus is  $2600 \text{ W/m}^2$ , which is much greater than the  $1360 \text{ W/m}^2$  available at Earth orbit. This nearly 100% increase in solar flux can significantly increase the performance of solar-powered vehicles. Even within or below the cloud layer there may be sufficient solar energy to power a vehicle. At the bottom of the cloud layer (45 km altitude), the solar intensity is between  $520$  and  $1300 \text{ W/m}^2$  depending on the wavelength of the radiation being collected. This is comparable to the solar intensity at Mars or Earth respectively. Therefore, even within the cloud layer, the ability to fly under solar power on Venus will be no worse than it is to fly on Earth or Mars.

The winds within the atmosphere blow fairly consistently in the same direction as the planetary rotation (East to West) over all latitudes and altitudes up to 100 km. Above 100 km, the winds shift to blow from the dayside of the planet to the night side. The wind speeds decrease as a function of altitude from  $\sim 100 \text{ m/s}$  at the cloud tops (60 km) to  $\sim 0.5 \text{ m/s}$  at the surface. These high wind speeds and the slow rotation of the planet produce a super rotation of the atmosphere (nearly 60 times faster than the surface). These high wind speeds and the slow rotation of the planet produce a super rotation of the atmosphere (nearly 60 times faster than the surface).

The gravitational acceleration on Venus ( $8.87 \text{ m/s}^2$ ) is slightly less than that on Earth, which aids somewhat in the lifting capability of an air vehicle. The atmospheric composition on Venus can also pose problems for the aircraft. The atmosphere is composed mostly of  $\text{CO}_2$  but also has trace amounts of corrosive compounds such as hydrochloric, hydrofluoric and sulfuric acids. (ref. 1) The atmospheric composition is given in table 2. Because of this composition, the speed of sound within the atmosphere is generally less than it is within Earth's atmosphere.

TABLE 2.—VENUS ATMOSPHERIC COMPOSITION (REF. 3)

Gas	Percent volume
Carbon dioxide (CO <sub>2</sub> )	96.5
Nitrogen (N <sub>2</sub> )	3.5
Sulfur dioxide (SO <sub>2</sub> )	150 ppm
Carbon monoxide (CO)	17 ppm
Water vapor (H <sub>2</sub> O)	20 ppm
Neon (Ne)	7 ppm
Argon (Ar)	70 ppm
Helium (He)	17 ppm

The main characteristics of the atmosphere (density, temperature, viscosity, solar attenuation, and wind velocity) are critical in determining the feasibility of flight within the Venus atmosphere. Models for these characteristics were used in the evaluation of the flight capabilities for the different platforms considered (refs. 4 and 5).

### Power System Options

The power required by the flight vehicle is given by the power needed to operate the onboard systems and payload and the power needed to overcome the drag generated and maintain flight. The systems and payload power are assumed to be fixed and constant throughout the flight. These are summarized in table 3.

TABLE 3.—ASSUMED SYSTEM POWER LEVELS

System	Continuous power level (W)
Communications	50
Control and operations	50
Payload	100

The power required to produce thrust is the other main power consuming component. Depending on the flight speed and environmental conditions the power required by the propulsion system will be the limiting factor in the vehicle's flight range and capabilities. A diagram of the propulsion system for the electric-powered vehicles is given in figure 2.

The operational efficiency associated with each of the components of the propulsion system is given in table 4. They are combined to get the driveline efficiency, which consists of all components up to the propeller. These efficiencies are representative approximations for each of the components under optimized operating conditions.

TABLE 4.—DRIVE LINE COMPONENT EFFICIENCIES

Component	Efficiency
Control electronics	$\eta_{mc}$ 0.98
Motor	$\eta_{em}$ 0.90
Gearbox	$\eta_g$ 0.90
Drive line efficiency	$\eta_p$ 0.794

The propeller efficiency has to be calculated based on a propeller sizing for the operational altitude and thrust requirement. The propeller efficiency was calculated based on the method outlined in references 4 and 5. This efficiency was usually in the range of 81 to 86%.

In addition to the components listed in figure 3, a heat exchanger was also needed by the system. The heat exchanger would add drag to the system and therefore affect the total power required. The heat exchanger drag is mostly a concern for the isotope-powered airship since a considerable amount of heat must be removed to the atmosphere. For the solar-powered airship it can be assumed that the heat exchanger size is zero.

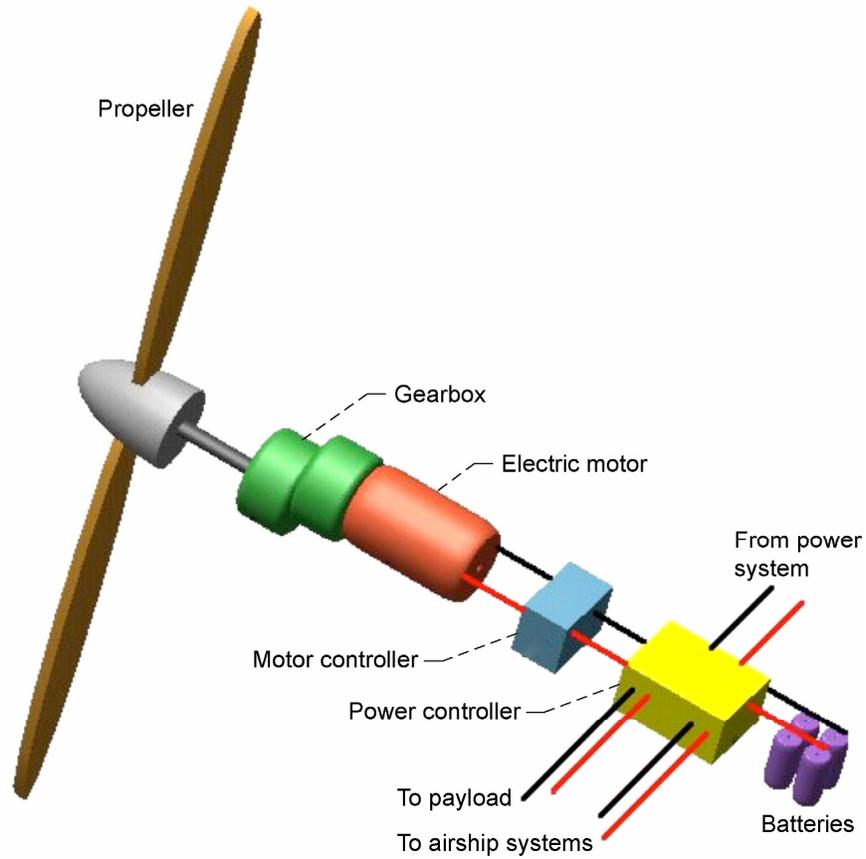


Figure 2.—Propulsion system drive train.

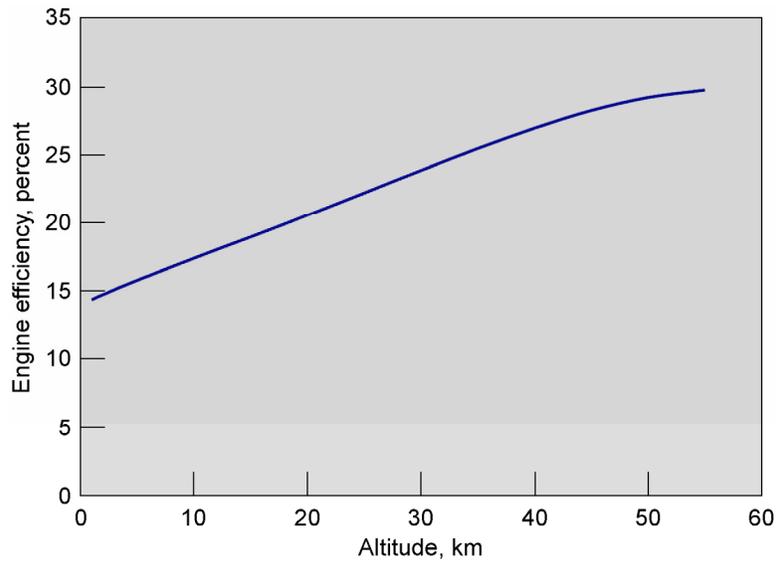


Figure 3.—Stirling engine efficiency as a function of altitude within the Venus atmosphere.

## Solar Power

Due to the thick atmosphere and abundant solar radiation above the cloud layer, both a solar-powered aircraft and airship can be considered for flight on Venus. Airships generate lift through buoyancy force whereas aircraft generate lift through the aerodynamics of fluid flow over the wings. If feasible, each type of vehicle would provide a means of controlled flight within the Venus atmosphere. Since the power for flight and operations comes solely from the sun, the feasibility of these vehicles will be based on a balance between the available power from the solar array and the power required to maintain flight. To provide the ability to station-keep, that is maintain position over a location on the surface, the vehicle will need to be capable of flying faster than the wind speeds at the flight altitude. If this is not possible the vehicle will still be capable of flight, however it will be continually blown backwards until it is blown onto the dark side of the planet where it will no longer be capable of generating power.

Operation within the upper atmosphere would be the best choice for a solar-powered air vehicle on Venus. At the altitude range where it can operate and station-keep, it is cold ( $-53\text{ }^{\circ}\text{C}$ ) and there is abundant sunlight. The cold temperature operation will enhance the performance of the solar array and the full solar spectrum is available so that conventional solar cells will operate fine. Although low altitude operation is being considered there are significant issues that would need to be addressed with getting a solar-powered air vehicle to operate near the surface of Venus. The main issue is the high atmospheric temperature. The high atmospheric temperatures near the surface will significantly degrade the performance of the solar array. Therefore it may be very difficult to produce any reasonable efficiency out of a solar array operating at such high temperatures. The second and equally critical issue is the operation of solar cells within the environment near the surface. In addition to the temperature, the spectrum of light reaching the surface is mostly on the red side of the spectrum due to the very thick atmosphere. Very little blue light reaches the surface. However it is this blue portion of the spectrum the most present day solar cells utilize in producing power. To take advantage of the light that does reach the surface, a new type of solar cell would need to be developed.

The performance characteristics used for the solar array in the subsequent analysis is given in table 5.

TABLE 5.—SOLAR ARRAY CHARACTERISTICS AND ASSUMPTIONS

Characteristic	Value
Solar cell efficiency (single crystal, $\eta_{sc}$ )	18% at $20\text{ }^{\circ}\text{C}$
Solar cell efficiency (thin film, $\eta_{sc}$ )	10% at $20\text{ }^{\circ}\text{C}$
Solar cell fill factor ( $S_{ff}$ )	80%
Array power conditioning efficiency ( $\eta_{pcn}$ )	95%

## Radioisotope Power

Another method for achieving long duration flight within the Venus atmosphere is to utilize a radioisotope heat source as a means of powering the vehicle. There are a number of conversion methods that can be utilized to produce power from the heat source. These methods are summarized in table 6 along with their present or near-term projected specific power.

TABLE 6.—NEAR-TERM CONVERSION SYSTEM SPECIFIC POWER AND EFFICIENCY

Conversion technology	Specific power (W/kg)	Conversion efficiency (%)
Thermoelectrics	4	7.5
Stirling heat engine	8	32
Thermophotovoltaics	5.1	15
Brayton	5.0	21

One of the more critical aspects to a flight vehicle's performance capabilities is its mass. Minimizing mass can provide significant benefits in altitude, range and flight duration. Because of this, the Stirling

heat engine was chosen as the conversion system in the analysis of the radioisotope-powered flight vehicle.

The conversion efficiencies shown in table 6 represents a base-line efficiency at the optimum design point operating temperature range. For this application the operating temperature range can vary considerably depending on the flight altitude of the airship. Therefore, for the Stirling engine, the conversion efficiency ( $\eta_e$ ) was expressed as a function of engine operating temperature ( $T_h$ ) and the heat rejection temperature ( $T_c$ ). This is given by equation (1). For the cycle the percent of Carnot or the maximum achievable efficiency ( $\eta_c$ ) was given to be 0.47.

$$\eta_e = \eta_c \left( 1 - \frac{T_c}{T_h} \right) \quad (1)$$

The operating temperature design point for the Stirling engine is a hot end temperature of 1123 K and a cold end temperature of 363 K. The ability to achieve this temperature range is dependent on the ambient temperature. The hot end temperature was fixed at the design point temperature. This was done because any changes to this temperature could have a significant effect on the engine's design due to material limitations. The cold end temperature was allowed to vary to accommodate the ambient temperature conditions. A  $\delta T$  of at least 50 K between the cold end temperature and the ambient temperature was required for the operation of the heat exchanger. Therefore, if the ambient temperature was not at least 50 K lower then the design point cold end temperature, the cold end temperature would be raised to maintain the 50 K  $\delta T$  between the atmosphere and the heat rejection temperature. This would have an effect of reducing the engine efficiency over the design point efficiency. Figure 3 shows the engine efficiency as a function of altitude within the Venus atmosphere.

The heat rejection temperature also sets the required heat exchanger area ( $A_{he}$ ). The heat exchanger area is also dependent on the environmental conditions (atmospheric temperature,  $T_a$ , atmospheric density,  $\rho_a$  and the specific heat of the atmosphere,  $c_p$ ), the airship operating requirements (required power output of the engine,  $P_r$  and its velocity,  $V$ ). The heat exchanger area and subsequent mass ( $M_{he}$ ) is given in equations (2) and (3) respectively.

$$A_{he} = \frac{P_r \left( \frac{1}{\eta_e} - 1 \right)}{\eta_{he} \eta_{hea} (T_c - T_a) \rho_a c_p V} \quad (2)$$

$$M_{he} = S_{he} A_{he} \quad (3)$$

Both the heat exchanger area and mass are also dependent on its efficiency ( $\eta_{he}$ ), its area efficiency ( $\eta_{hea}$ ), that is the percentage of frontal area in which the air can actually pass through which takes into items such as the frame and support structure and its specific mass ( $S_{he}$ ) that are characteristics of its design. For this analysis the efficiency was assumed to be 80% and the specific mass was assumed to be 11.18 kg/m<sup>2</sup>.

Solving for the heat exchanger area is an iterative process because the heat exchanger area affects the vehicle drag, which in turn affects the power required from the engine and therefore the heat exchanger area. The drag produced by the heat exchanger is given by equations (4) and (5). Where equation (5) represents the density of the atmosphere after passing through the heat exchanger ( $\rho_{he}$ ).

$$D_{he} = A_{he} \left( 3.28 \frac{\rho_a}{\rho_{he}} - 1.72 \right) \quad (4)$$

$$\rho_{he} = \frac{\rho_a T_a}{0.2T_a + 0.8T_c} \quad (5)$$

As with the solar vehicles, both airships and aircraft were considered for radioisotope-powered flight. Each was evaluated from the surface to the upper levels of the Venus atmosphere.

### Airship Flight on Venus

The thick atmosphere of Venus can provide significant buoyancy for the generation of lift. However, other characteristics of the environment such as thick cloud cover, high atmospheric temperature below the cloud layer, and the high winds within the upper atmosphere, can make operating an airship within the atmosphere difficult. The evaluation of an airship was performed to determine if these environmental constraints could be overcome, and if so, what would be the necessary size and operating range of the airship for each type of power system being considered. To begin the evaluation, a basic airship configuration had to be assumed. The configuration chosen consists of a standard cylindrical shape with three tail fins and two propulsion pods. For the solar-powered airship, solar arrays were located on the upper surface of the airship envelope and on the tail fins. This basic layout is shown in figure 4.

Using the atmospheric environmental conditions, the operation of sizing an airship was performed from the surface to the upper atmosphere.

The power required by the airship is given by the power needed to operate the onboard systems and payload and the power needed to overcome the drag on the airship and maintain station over a specified location. Due to the very low wind speeds near the surface of Venus, the majority of the power consumption of the airship comes from systems within the ship. These assumed power requirements are given in table 4.

The power for propulsion was estimated using the method given in reference 5. Due to the high-density environment of the Venus atmosphere, the lift produced by the envelope volume was more than sufficient to lift the airship and its associated systems. Because of this, the mass scaling of the airship is not a critical factor in the analysis.

For the solar-powered airship, the output of the solar array was calculated based on the incident solar radiation on the array (ref. 6). The incident radiation is dependent on the shape of the array and the attenuation due to the atmosphere. Because of the thick atmosphere and cloud cover, it was assumed that all solar radiation below the clouds was diffuse. Therefore, there was no variation in array output based on array or airship position relative to the location of the sun. The array output or power available was calculated and used to determine if there was sufficient power to operate the airship. The power required for maintaining station above a specific location and the power available from the solar array was

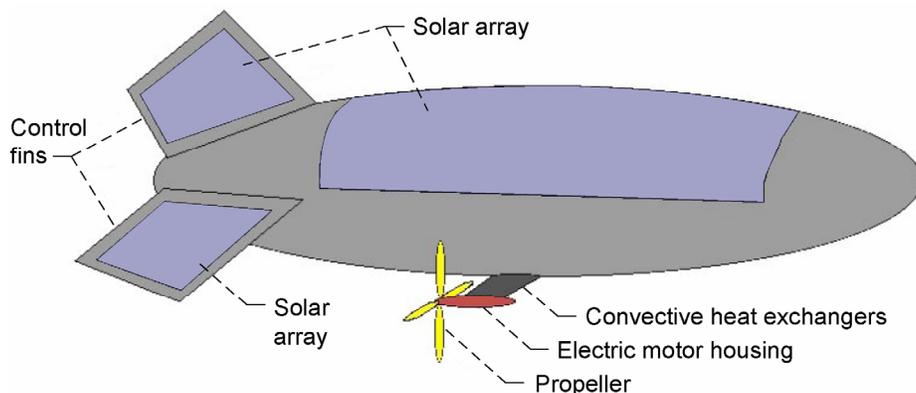


Figure 4.—Venus airship configuration.

determined for airship sizes up to 20 m in length. Airships larger than 20 m in length were deemed not reasonable for autonomous deployment and operation within the Venus atmosphere. The power required and available was calculated from near the surface up to an altitude of 50 km. These results are shown in figure 5.

From this figure it can be seen that there is a sharp rise in required power that occurs near 10 km in altitude. This rise in required power, as seen in figure 6, is due to the increasing wind speeds that occur with increasing altitude. Because of this significant rise in the power required to maintain station, it is not feasible to station-keep a solar-powered airship, of the sizes examined, above approximately 10 km in altitude. Below this altitude, the required airship size necessary to operate within the Venus environment was determined and is given in figure 6. This figure shows required airship size for altitudes up to 9 km.

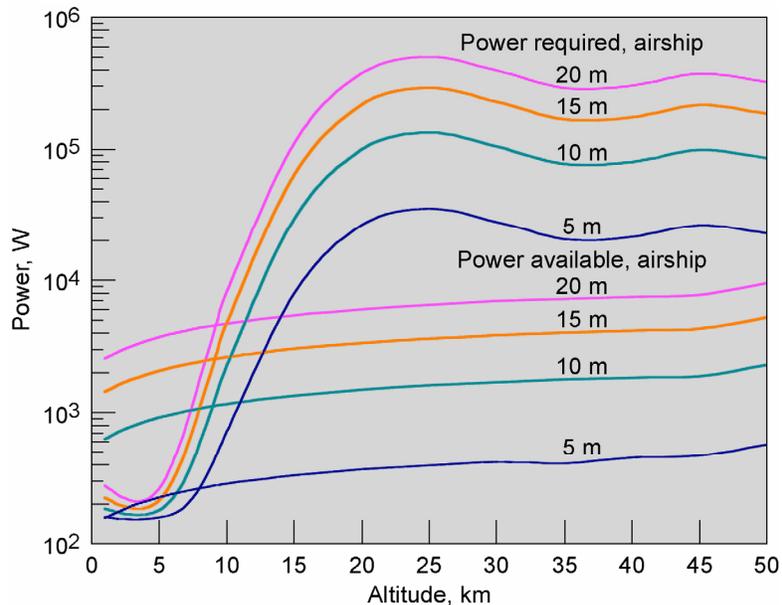


Figure 5.—Power available and power required for various size solar-powered airships.

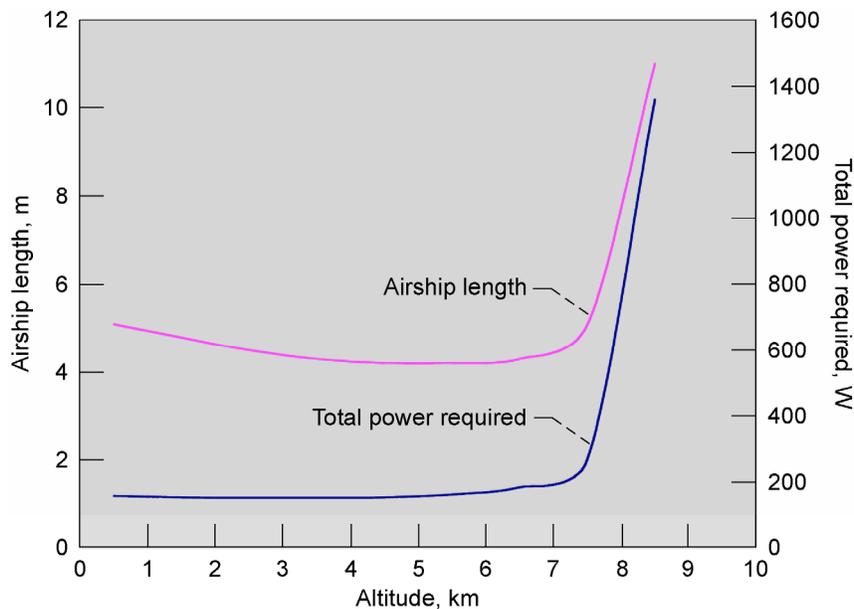


Figure 6.—Total power and airship size as a function of altitude on Venus for a solar-powered airship.

If the requirement to station-keep is eliminated then the airship can be utilized at higher altitudes. In this case however, the airship will be blown backwards and eventually move into the dark side of the planet. The rate at which the airship will move backwards will depend on the wind speed and atmospheric density at the flight altitude. If it is assumed that the airship begins its flight at dawn the total flight duration until it reaches dusk can be calculated. To calculate this the velocity at which the airship can fly at a given time of the day and altitude the available power has to be determined. This available power will vary throughout the day due to the change in the sun angle as that airship moves from dawn to dusk.

The calculation of instantaneous available power ( $P_i$ ) is given in reference 4. From this power level the instantaneous flight velocity ( $V_{fi}$ ) can be calculated. This forward flight velocity is based on the propulsion system efficiency, airship volume ( $V_{as}$ ), volumetric drag coefficient ( $c_{dv} = 0.0266$ ) and the atmospheric density ( $\rho$ ) and is given by equation (6).

$$V_{fi} = \left( \frac{2P_i \eta_p}{\rho c_{dv} V_{as}^{2/3}} \right)^{1/3} \quad (6)$$

The corresponding airship instantaneous velocity ( $V_i$ ) relative to the surface is given by equation (7).

$$V_i = V_w - V_f \quad (7)$$

From equations (6) and (7) the total flight time for the airship can be calculated by summing each incremental distances traveled ( $D_i$ ) at a given velocity. This is given by equation (8).

$$t_f = \sum_{i=1}^{i=n} \frac{D_i}{V_i} \quad (8)$$

Total flight time is shown in figure 7 for various size solar-powered airships. On this figure is also plotted the lifting capacity in kilograms of the various size airships as a function of altitude.

From figure 7 it can be seen that significant flight time can be achieved just above the maximum station-keeping altitude for each size airship. This decreases rapidly due to increasing wind speeds up to an altitude of around 20 km and then levels off due to the decreasing atmospheric density. However, as the atmospheric density decreases so does the lifting capacity. This reduction in lifting capacity is what eventually limits the maximum altitude for a given size airship.

The method described above was also used to evaluate an isotope-powered airship for flight on Venus. The main difference in the analysis between the solar and radioisotope -powered airships is that for the radioisotope-powered airship the total mass needs to be considered. This is because the available power, which is dependent on the airship size, was driving the solar-powered airship sizing. Where as for the radioisotope-powered airship, the airship mass and flight altitude drives the airship sizing. To calculate the airship mass the relations for estimating the mass of the various components given in reference 5 were used.

The results of this analysis are shown in figure 8. Above about 11 km in altitude there were no airship solutions that converged for either mass or power. Therefore, based on this analysis, the isotope-powered airship is not feasible on Venus for a station-keeping mission above 11 km altitude.

Below 11 km it was possible to maintain station with a reasonable size airship. Even though the temperatures are very high near the surface, the very thick atmosphere enables sufficient heat transfer from the isotope engine. At around 10 km in altitude the airship size and power requirements increase significantly. As with the solar-powered airship, this is due to the increase in wind speed that occurs at these altitudes. For a low altitude exploration vehicle, the isotope-powered airship holds promise for use on Venus. It is better suited to high temperature operation than the solar-powered airship and, as an additional benefit; its required size is smaller.

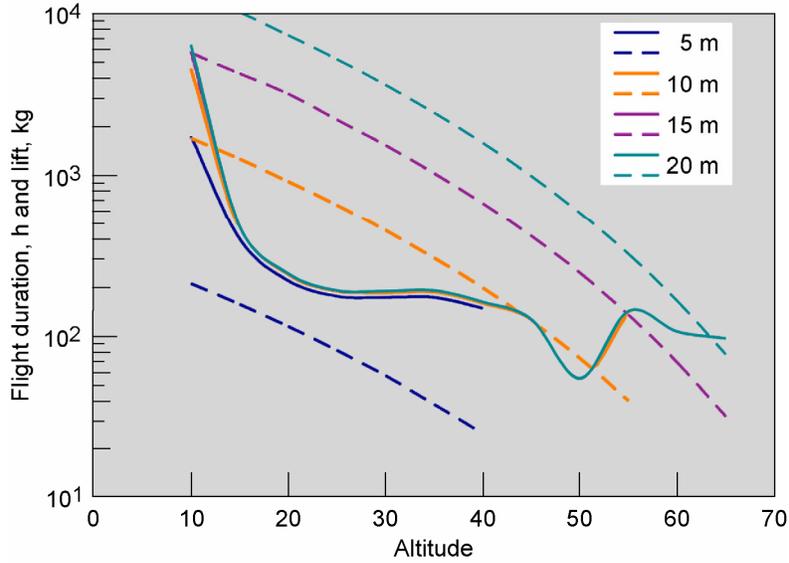


Figure 7.—Maximum flight duration and lifting capacity for a solar-powered airship above the station-keeping altitude. Solid lines represent duration and dashed lines represent lift.

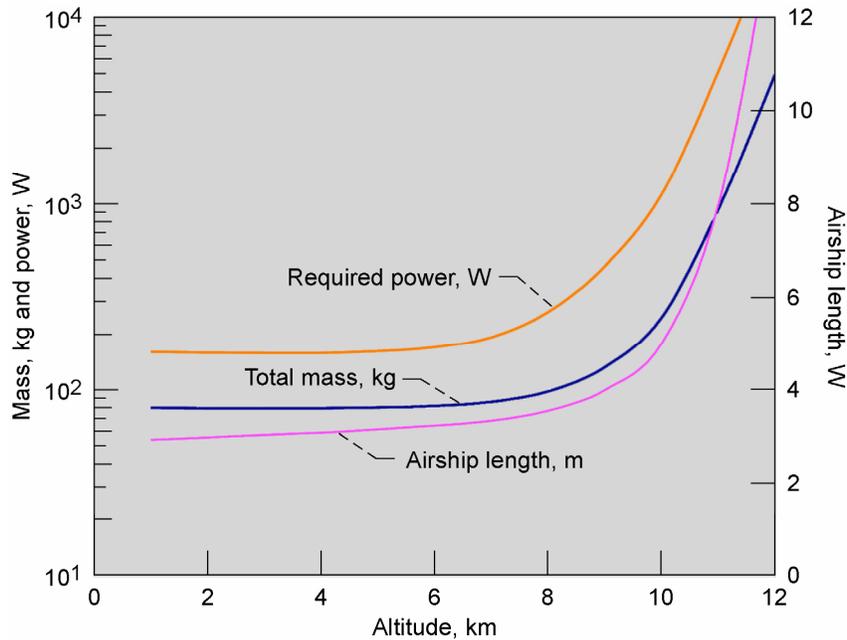


Figure 8.—Mass, power and length of an isotope-powered airship on Venus.

As with the solar-powered airship, if the station-keeping requirement is eliminated then higher altitudes can be achieved. However, unlike the solar-powered airship, the radioisotope-powered airship will still have an unlimited duration even if it is not able to station-keep. So as long as the airship can achieve a particular altitude it can maintain that altitude indefinitely. The maximum achievable altitude as a function of airship size is given in figure 9.

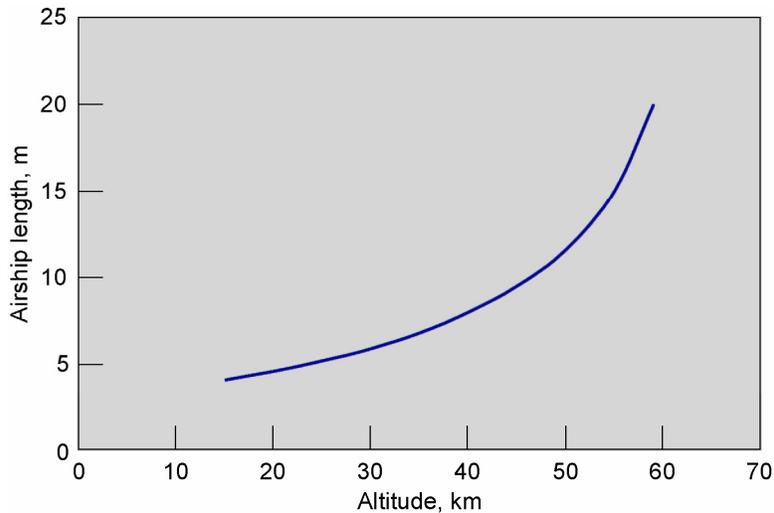


Figure 9.—The maximum achievable altitude for non-station-keeping radioisotope-powered airship.

## Aircraft Flight on Venus

As with the airship, both solar and radioisotope-powered vehicles can be considered for flight within the Venus atmosphere. For a solar-powered aircraft, the flight altitude and aircraft size will depend on the power balance between the available power from the solar array and the drag of the aircraft due to flight at the velocity of the wind. A radioisotope-powered aircraft will be limited by the aircraft mass and the ability to generate sufficient lift to maintain flight. The aircraft configuration chosen is a standard wing-tail arrangement with an electric motor driven propeller propulsion system, as shown in figure 10.

For the solar-powered aircraft, the first step in addressing the aircraft's size and flight altitude is determining the amount of power available for flight. The main power source for the aircraft is the sun. Photovoltaic arrays convert sunlight into electricity, which is either stored in the silver-zinc battery or utilized directly for the aircraft operation. The amount of solar energy available is dependent on the location (or latitude) of the aircraft, the time of year, and any atmospheric attenuation (due to clouds, haze or dust). For the aircraft to operate, the power requirements will need to be less than what is available from the solar arrays. The power requirements include the power needed to generate thrust and the operational power given in table 3.

Based on the environmental characteristics and the solar array performance, the available power as a function of wing area can be determined (ref. 4). This calculated available power, in conjunction with the power required, is used to determine the flight capability of the aircraft at a given altitude. Because both the aircraft's available power (available solar flux) and its required power (velocity needed to maintain lift or station) are dependent on the environment, sizing the aircraft for flight is an iterative process between variations in flight altitude and latitude and in the size of the aircraft (ref. 4). Unlike the solar-powered airship, the total mass of the solar-powered aircraft is a critical factor in its feasibility. The mass determines the amount of lift that is needed, which in turn sets the cruise speed of the aircraft and therefore required power. The mass sizing for the solar aircraft is given in reference 4.

The aircraft sizing would scale proportionally with wingspan. The aircraft sizes, represented by their wingspans, that were considered were 6, 9, and 12 m. The aspect ratio for each was 5. The initial flight envelope for a station-keeping mission was determined by calculating the power required by the aircraft to fly at a speed equal to the wind speed plus the systems power requirements and comparing that to the power available from the solar array for continuous operation. Figure 11 presents curves that show power required and power available over the altitude range from the surface up to 80 km for each aircraft size considered.

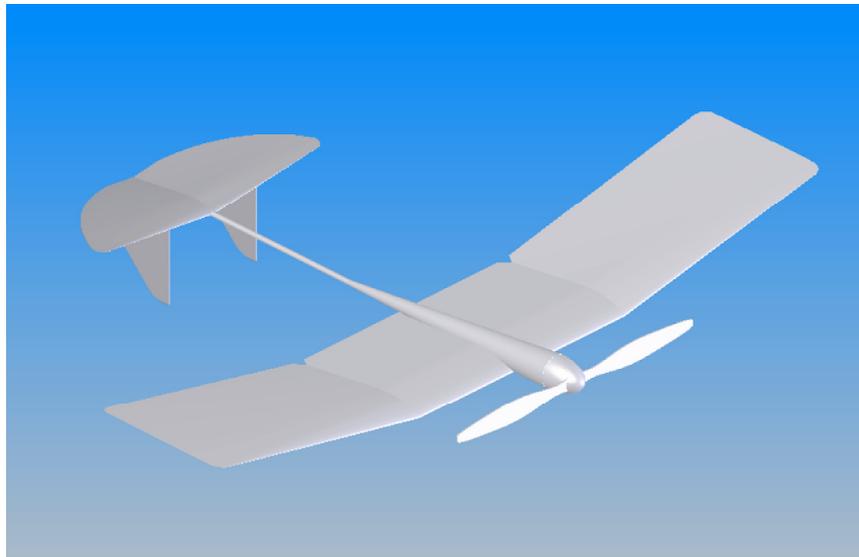


Figure 10.—Venus aircraft conceptual drawing.

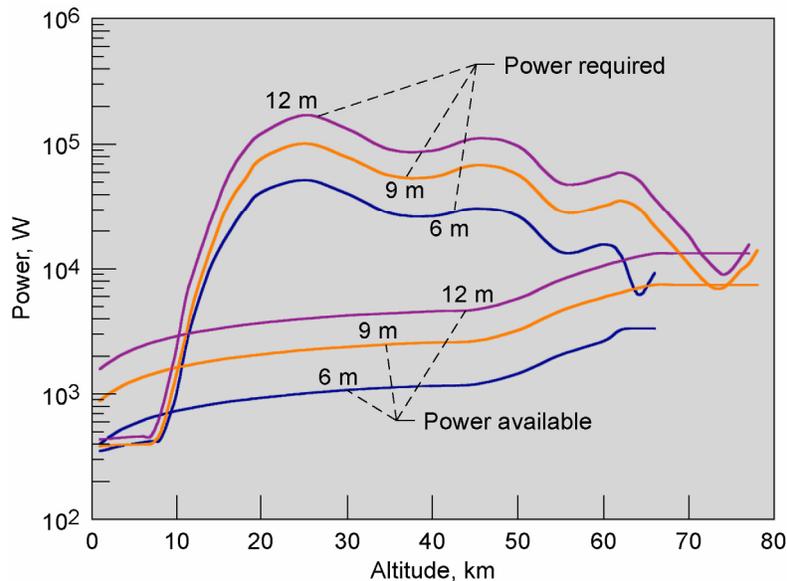


Figure 11.—Solar aircraft power available and power required.

From this figure it can be seen that over most of the atmospheric altitude range, from about 10 to approximately 72 km, a solar-powered aircraft will not have sufficient power to station-keep. Below 10 km in altitude, the curve indicates that there is abundant power for flight. This is due to the very low wind speeds near the surface of the planet. However in this region, the power available curves are very optimistic. As mentioned previously, the ability for the solar array to operate within the high temperature environment with light concentrated mainly in the red end of the spectrum is highly questionable.

There is a second region, upwards of 70 km in altitude, where there is sufficient power to fly faster than the wind speeds. The altitude range where this is feasible depends on the aircraft size. For the aircraft sizes examined, the 9 and 12 m wingspan aircraft were capable of faster than wind flight within this upper region, whereas the 6 m wingspan aircraft was not. A close-up of the power required and available curves over this altitude region is shown in figure 12. A baseline design point is indicated on this figure. This

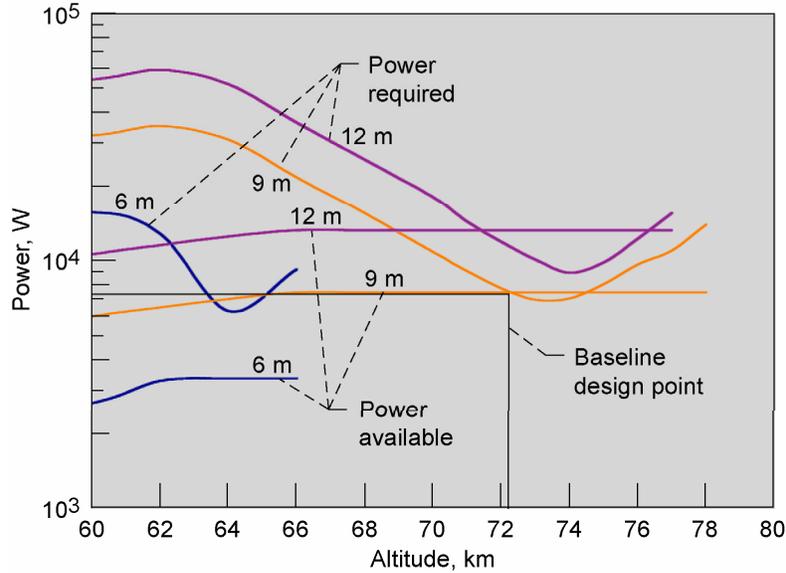


Figure 12.—Venus solar aircraft baseline design point.

design point represents a reference solar-powered aircraft configuration that is capable of sustained flight over a single location on Venus.

An analysis was also performed to determine the altitude range and maximum flight duration achievable if there was no station-keeping requirement. Under these conditions the aircraft would fly into the winds and be slowly blown backwards until it reached a point where the sun elevation angle was too low to provide the necessary power to fly. The flight duration under these conditions would be dependent on the power available to the propulsion system and the corresponding velocity that could be achieved at that power level. The velocity achievable at the available power would need to be sufficient for producing enough lift to maintain flight. Whereas the airship would be capable of operating from dawn to dusk, the aircraft would only be capable of operating where the power available can meet the velocity requirements for flight. The achievable velocity for a given instantaneous power level ( $P_i$ ) and aircraft size (set by the wingspan,  $b$ ) is given by equation (9). This equation is solved iteratively for the instantaneous flight velocity  $V_i$ .

$$P_i = \left( \frac{\rho_a S_w c_f V_i^3}{2} + \frac{2(Mg)^2}{\pi \rho_a e b^2 V_i} \right) \frac{1}{\eta_p} \quad (9)$$

The aircraft wetted surface area ( $S_w$ ), given in equation (10), is based on the wingspan and aspect ratio ( $A_R$ ) for the aircraft. The efficiency factor used for the wing ( $e$ ) and the friction coefficient ( $c_f$ ) were 0.9 and 0.0049 respectively (ref. 4).

$$S_w = 2 \frac{b^2}{A_R} 1.3 \quad (10)$$

The aircraft mass ( $M$ ) and the gravitational force on Venus ( $g$ ) determine the lift needed. Approximations were produced to size the airframe mass ( $M_{af}$ ) and propeller mass ( $M_p$ ) as functions of wing-span. These are given in equations (11) and (12) respectively. Utilizing these and expressions and those for the various other aircraft components, given in reference 4, the aircraft mass as a function of the wingspan and maximum available power throughout the flight ( $P_m$ ) was derived. This expression for mass is given in equation (13).

$$M_{af} = 31.343 - 3.3846b + 0.54144b^2 - 0.009422b^3 \quad (11)$$

$$M_p = 6.688 - 1.6578b + 0.1588b^2 - 0.001971b^3 \quad (12)$$

$$M = 79.9241 - 5.54664b + 0.990264b^2 - 0.0125323b^3 + 3.1714E - 3P_m \quad (13)$$

The flight time is determined by summing the incremental flight times calculated by the instantaneous flight velocity and the distance traveled at that velocity, as given in equation (8). Using this method the flight duration as a function of altitude was calculated for the same aircraft sizes used in the station-keeping analysis. These results are shown in figure 13.

The results for the non-station-keeping solar-powered aircraft show that as the altitude increases the flight duration decreases. However, as with the airship, the low altitude operation may be optimistic due to the questionable ability for the solar array to operate in the high temperature red spectrum light available near the surface. At higher altitudes, the duration begins to increase for the two larger aircraft sizes examined. This should be expected, since there is a solution for the station-keeping or infinite duration flight time above 70 km for both larger aircraft. One interesting note is that the curves for both the 9 and 12 m wingspan aircraft are very similar. This indicates that increasing the aircraft size will not continually produce more capable aircraft for the non-station-keeping mission.

A radioisotope-powered aircraft was also considered for flight within the Venus atmosphere. With the radioisotope-powered aircraft its size or wingspan is no longer coupled to its power generation capability as it is with the solar-powered aircraft. Therefore the power system for the aircraft was scaled to meet the power requirements for a given size aircraft to fly at a specific altitude. The power system has to supply the power for the vehicle systems and payload given in table 3 as well as the power to the propulsion system to maintain flight. The propulsion system power required is based on the power needed to overcome the aircraft drag. This drag is broken into three main components: the friction drag of the aircraft moving through the atmosphere, the induced drag due to the generation of lift, and the parasite drag which in this case is mainly composed of the power system radiator. The total aircraft drag ( $D$ ), which is the sum of these three components, is given by equation (14).

$$D = \rho_a V^2 \left( \frac{b^2}{A_R} (1.25c_f + 0.5c_d) + D_{he} \right) \quad (14)$$

The flight velocity ( $V$ ) was the greater of either the velocity needed to maintain flight, given in equation (15), or the wind velocity at the flight altitude plus a small margin of 1 m/s for maneuverability.

$$V = \sqrt{\frac{2MgA_R}{\rho_a b^2}} \quad (15)$$

The induced drag coefficient due to the generation of lift ( $c_d$ ) was based on the lift to drag curve for the E214 airfoil, shown in figure 14. Curve fits for the lift coefficient ( $c_l$ ) as a function of angle of attack ( $\alpha$ ) and drag coefficient as a function of lift coefficient are given in equations (16) and (17) respectively. This airfoil was selected for the aircraft because it had good flight characteristics at the estimated Reynolds number at which it would be flying within the Venus atmosphere. An angle of attack of  $6^\circ$  was selected for the wing at cruise flight conditions. This operating point is near the minimum drag point for the airfoil and still produces sufficient lift.

$$c_l = 0.20979 + 0.10458\alpha + 8.5706E - 4\alpha^2 - 2.13E - 4\alpha^2 \quad (16)$$

$$c_d = 0.013323 - 0.014906c_l + 0.0014092c_l^2 + 0.015184c_l^3 \quad (17)$$

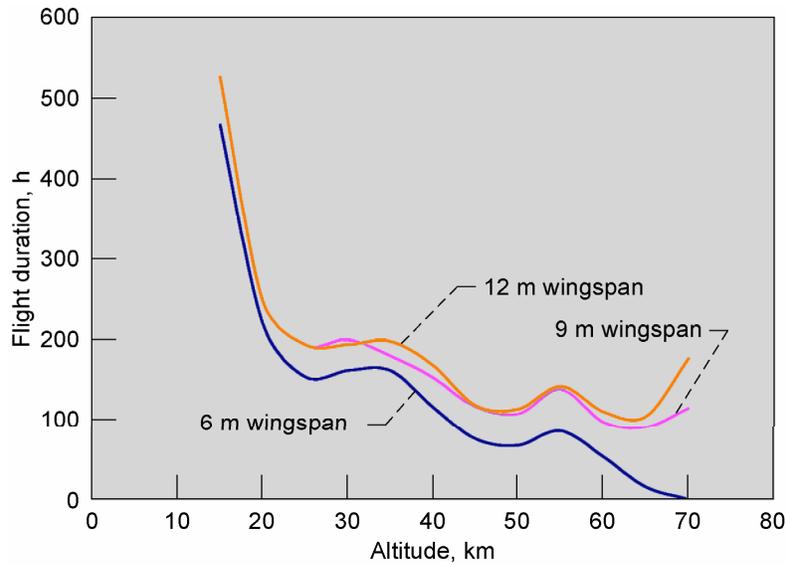


Figure 13.—Flight duration for a non-station-keeping solar-powered aircraft.

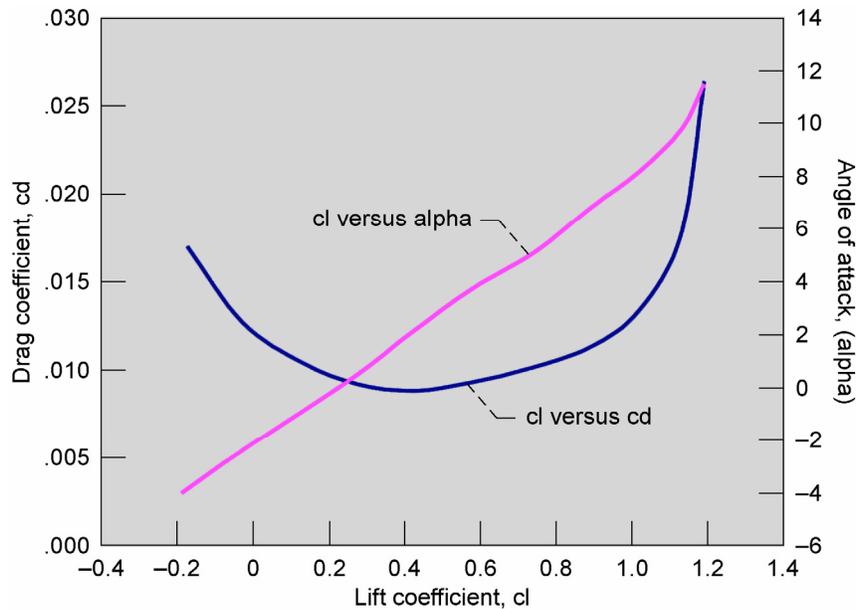


Figure 14.—Operational curves for the E225 airfoil.

The heat exchanger area and the drag due to the heat exchanger were calculated from equations (2) and (4) respectively.

The next aspect of the aircraft that has to be determined is its total mass. The mass of the various components of the aircraft and its systems were calculated utilizing the relations given in reference 4. The masses of the components of the power and propulsion system were calculated utilizing the relationships given in reference 5 for the radioisotope/Stirling power system.

Sizing the aircraft based on the required power, aircraft total mass and total drag was an iterative process. Utilizing this analysis approach initial results were generated for a station-keeping mission where the aircraft is capable of flying at or faster than the wind speed at a specific altitude. Since the power production capability is not coupled to the size of the aircraft, the flight capabilities can be determined by

either using the minimum power or the minimum aircraft size required for flight at a specific altitude. This tradeoff between size and power is shown in figure 15 for flight at an altitude of 8 km.

As mentioned previously, the aircraft scales proportionally with wingspan. Therefore the wingspan is used as a measure of overall aircraft size. The power, mass and velocity curves all correspond to aircraft sizes that are capable of flight. From this figure it can be seen that there is a specific aircraft size (wingspan of 6.0 m) that produces a minimum required power. This occurs at a point where the aircraft's cruise speed is equal to the wind speed. Although smaller size aircraft have less drag, they must fly faster in order to maintain flight and therefore their required power and mass increase. However, larger aircraft do not get any advantage of reducing flight speed because they still need to fly faster than the wind speed in order to maintain station over a specific ground location. So for aircraft larger than the minimum power size, their power requirement and mass also increase. There is also a size that represents the smallest aircraft (wingspan of 3.5 m) that is capable of flight at this altitude. This aircraft has much greater power requirements and flies at a higher velocity but it is still capable of carrying the same mission requirements.

The difference in selecting between these two design points will depend on the mission requirements. If the stowage size and deployment were the main critical issues, then the minimum size aircraft would be the desired design point. However if minimizing the amount of isotope required by the power system is critical then the minimum power point would be more desirable. Flight altitude capabilities for both the minimum power and minimum size aircraft are shown in figures 16 and 17 respectively.

For both minimum power and minimum size designs the maximum achievable altitude was approximately 15 km. Above this altitude, the power requirement due to the higher wind speeds produced an aircraft that was too heavy to maintain flight. This can be seen, in both figures, by the significant increase in required power above 12 km in altitude.

The wingspan for the minimum power aircraft sizing is larger at lower altitude, due to the low flight speed, and reaches a minimum at between 10 and 12 km altitude. Above 12 km it then begins to increase again due to the increasing lift requirements. Whereas the wingspan for the minimum size aircraft increases slowly up to approximately 12 km and then begins to increase at a greater rate, also due to increasing lift requirements. It is interesting to point out that at approximately 11 km in altitude the minimum power and size designs are the same. This can be looked at as a somewhat optimum flight altitude for a radioisotope-powered aircraft on Venus.

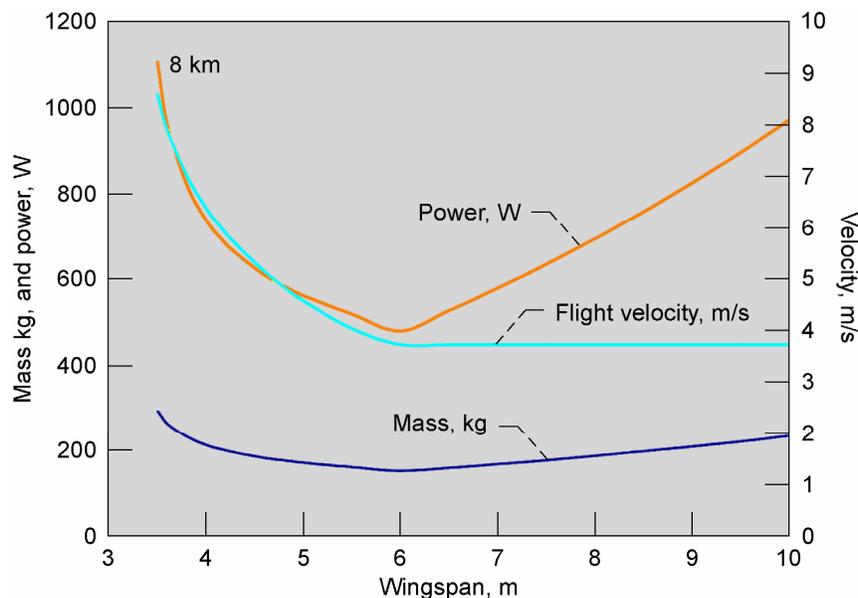


Figure 15.—Aircraft mass and power required as a function of wingspan.

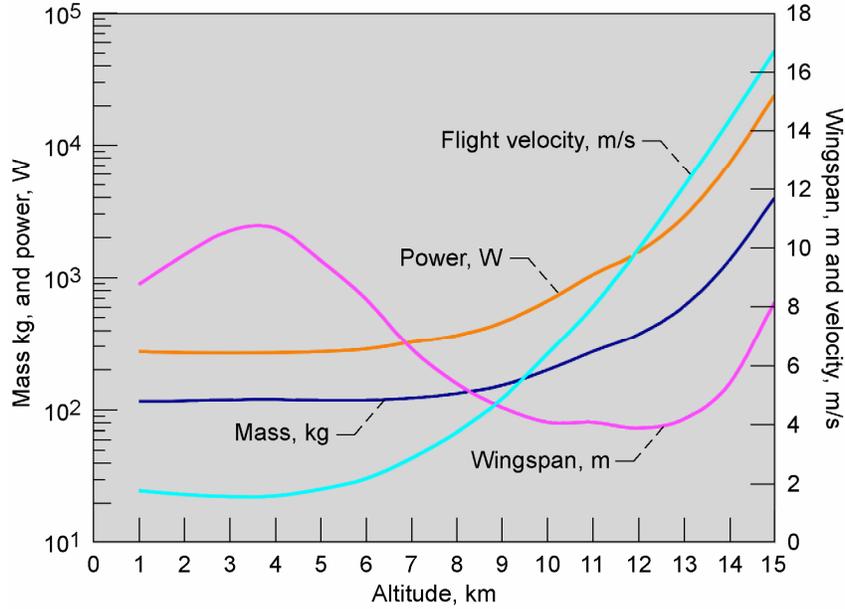


Figure 16.—Requirements for minimum power radioisotope-powered aircraft flight.

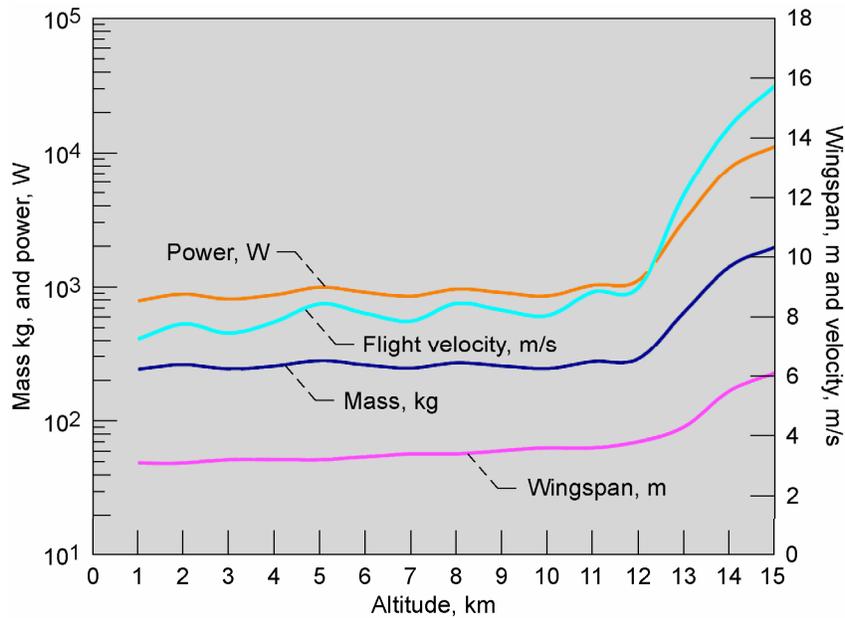


Figure 17.—Requirements for minimum size radioisotope-powered aircraft flight.

Similar to the other vehicles examined in this analysis, if the station-keeping requirement is removed, the flight altitude range for the radioisotope-powered aircraft will increase significantly. Unlike the solar-powered aircraft the mission duration of the radioisotope-powered aircraft will still be unlimited even if it cannot station keep. The maximum altitude achievable for a non-station keeping radioisotope-powered aircraft is shown in figure 18. From this figure it can be seen that altitudes of over 50 km are achievable with wingspans of 20 m or less. Also shown on this curve is the required flight velocity for the aircraft

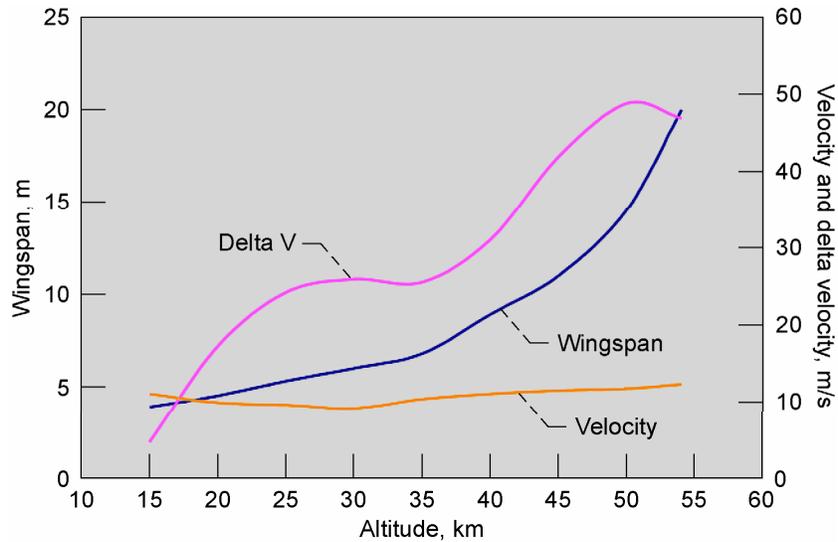


Figure 18.—The maximum achievable altitude and flight velocity for non-station-keeping radioisotope-powered aircraft.

and the difference in that flight velocity and the wind speed (delta velocity) at a given altitude. This delta velocity is essentially how fast the aircraft will be blown backwards with respect to a location on the surface. Although the aircraft would effectively be moving backwards, it will still be controllable and could provide unique science data on its journey around the planet.

## Summary

The results presented above for both the airship and aircraft show that long duration flight possible within different regions of the atmosphere for each type of vehicle. For the solar-powered vehicles, the airship was only capable of flight near the surface below 10 km in altitude whereas the solar-powered aircraft was capable of long duration flight at a small region above 70 km in altitude as well as near the surface. The low altitude operation of the solar-powered vehicles is however questionable. This is due to the operation of the solar array in the high ambient temperatures and with the very red spectrum of available light. Present day solar cells cannot operate under those conditions. Therefore for the solar-powered vehicles to be applicable to low altitude flight a new type of solar cell would need to be developed that could withstand the temperature and utilize the red end of the light spectrum to produce power. Based on this the high altitude operation of the solar-powered aircraft is the only likely application of a long-duration solar-powered flight vehicle on Venus.

For the radioisotope-powered vehicle both the airship and aircraft were capable of performing station-keeping missions below 15 km in altitude. Their operation at the high temperatures near the surface is much more feasible than the photovoltaic system. Also if the station-keeping requirement is removed the aircraft at a reasonable size was capable of operating well up into the atmosphere (below 55 km). Although at these higher altitudes it would not be able to maintain station over a specific location on the ground, it would still be capable of long duration flight because its power is not dependent on the sun as it is with the solar-powered aircraft. Based on these results a reasonably sized radioisotope-powered aircraft (on the order of a 10 m wingspan) would be capable of operating near the surface and up into the mid-atmosphere levels. This type of vehicle could provide significant insight into the atmosphere of Venus as well as a unique means of exploring and imaging the surface.

## References

1. Landis, G.A., Colozza A.J., LaMarre, M.C., “Atmospheric Flight on Venus,” NASA/TM—2002-211467, June 2002.
2. Windows to the Universe, at <http://www.windows.ucar.edu/>, University Corporation for Atmospheric Research, July 2002.
3. “Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development 1982 Revision (vol. 1),” NASA TM–82478, January 1983.
4. Colozza, A.J., “Solar-powered Flight on Venus,” NASA/CR—2004-213052, April 2004.
5. Colozza, A.J., “Airships for Planetary Exploration,” NASA/CR—2004-213345, November 2004.
6. Colozza, A.J., “Initial Feasibility Assessment of a High Altitude Long Endurance Airship,” NASA contractor report, under publication, October 2003.

<b>REPORT DOCUMENTATION PAGE</b>			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
<b>1. AGENCY USE ONLY</b> <i>(Leave blank)</i>	<b>2. REPORT DATE</b> November 2006	<b>3. REPORT TYPE AND DATES COVERED</b> Technical Memorandum		
<b>4. TITLE AND SUBTITLE</b>  Evaluation of Long Duration Flight on Venus			<b>5. FUNDING NUMBERS</b>  WBS 22-390-30-20	
<b>6. AUTHOR(S)</b>  Anthony J. Colozza and Geoffrey A. Landis				
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  E-15716	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>  NASA TM-2006-214452	
<b>11. SUPPLEMENTARY NOTES</b> Anthony J. Colozza, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142; Geoffrey A. Landis, NASA Glenn Research Center. Responsible person, Anthony J. Colozza, organization code RPC, 216-433-5293.				
<b>12a. DISTRIBUTION/AVAILABILITY STATEMENT</b>  Unclassified - Unlimited Subject Categories: 07, 05, and 91  Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a>  This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT</b> <i>(Maximum 200 words)</i>  An analysis was performed to evaluate the potential of utilizing either an airship or aircraft as a flight platform for long duration flight within the atmosphere of Venus. In order to achieve long-duration flight, the power system for the vehicle had to be capable of operating for extended periods of time. To accomplish these, two types of power systems were considered, a solar energy-based power system utilizing a photovoltaic array as the main power source and a radioisotope heat source power system utilizing a Stirling engine as the heat conversion device. Both types of vehicles and power systems were analyzed to determine their flight altitude range. This analysis was performed for a station-keeping mission where the vehicle had to maintain a flight over a location on the ground. This requires the vehicle to be capable of flying faster than the wind speed at a particular altitude. An analysis was also performed to evaluate the altitude range and maximum duration for a vehicle that was not required to maintain station over a specified location. The results of the analysis show that each type of flight vehicle and power system was capable of flight within certain portions of Venus's atmosphere. The aircraft, both solar and radioisotope power proved to be the most versatile and provided the greatest range of coverage both for station-keeping and non-station-keeping missions.				
<b>14. SUBJECT TERMS</b>  Solar powered aircraft; Venus atmosphere, Stirling engines; Radioisotope heat source; Aircraft design; Aircraft performance; Airships			<b>15. NUMBER OF PAGES</b> 26	
			<b>16. PRICE CODE</b>	
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b>	



