GONDOLA DESIGN FOR VENUS DEEP-ATMOSPHERE AEROBOT OPERATIONS

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Abstract

Aerobots are Aeronautical RoBOTS with autonomous navigation capabilities. An aerobot mission has been proposed for exploration of the upper atmosphere through the near-surface regions of Venus. The wide range of atmospheric conditions from the relatively benign upper atmosphere to the hot, high-pressure surface requires thermal protection of the scientific instruments, and the mass constraints of a balloon system require that the thermal protection system be lightweight. To meet the thermal control challenges, we propose use of lightweight vacuum dewar technology combined with a phase-change material (PCM) thermal damper. For the proposed aerobot mission, the total thermal control mass is estimated to be 7.9 kg, and the entire gondola can weigh 25 kg, leaving 8.3 kg for science instruments and communication hardware. Four kilograms of PCM are required to provide a repeatable 15-hour mission sequence that includes a 3.5-hour descent to the surface, 1 hour of surface operations, a 2.5-hour ascent to the cooler upper atmosphere, and 8 hours to refreeze the PCM.

Lastly, aerobot system design tradeoffs are discussed, and the extension of vacuum dewar/PCM technology to outer planet probes is explored.

Introduction

In 1985, the **Vega/Venera program**, a French/Russian/US initiative, sent two balloons and two landers to Venus. The balloons floated for 1-2 days at 54 km and concentrated primarily on atmospheric science. The landers made a 60-minute descent to the surface where measurements were taken for about 2 hours. The landers focused on surface geoscience at single sites and had limited operational life due to the harsh surface environment at Venus. No subsequent in *situ* surface explorations of Venus have been attempted. Now, it is desired to provide a vehicle with the capability for (a) repeated descents to the Venusian surface, (b) autonomous navigation toward specific targets of scientific interest, and (c) long-term *in situ* atmospheric measurements. The justification for developing such a vehicle is scientific measurements that could be made with the platform. In particular, data are desired on volcanic and tectonic processes and atmospheric dynamics. These data that would improve our knowledge of the geologic and thermal evolution of Venus.[1] This paper describes thermal control and instrument protection strategies for an aerobot (Aeronautical roBOT) that would provide the above capabilities.

Aerobots

Aerobots with surface descent capabilities provide a unique opportunity to advance our understanding of the surface *and* atmosphere of planets with significant atmospheres. Of the bodies in the solar system with substantial atmospheres, Venus, Earth, Mars, Jupiter, Saturn's moon Titan, and the outer planets are most favorable for aerobot missions. Venus, Earth, and Titan have tropospheric atmospheres which allow the use of phase-change balloon altitude control strategies as an autonomous navigation tool.[2] By using knowledge of wind headings at various altitudes and on-board computer-based path planning algorithms, these altitude control strategies offer the possibility of zero-power autonomous navigation at other planets. The only energy required is the power to operate anon-board minicomputer. Recent Earth-based flights have demonstrated the feasibility of aerobot vertical mobility control strategies.[3]

The control over vertical mobility is accomplished with Phase-Change Fluids (PCFs) which exist as vapor at low altitude conditions and as liquids at high altitude conditions. The aerobot's vertical motion is caused by buoyancy modulation associated with volume change as the PCF vaporizes or condenses. To achieve such behavior, the aerobot's mass and volume are closely balanced such that a phase change from liquid to vapor is enough to reverse system motion from downward to upward. At low altitudes the PCF vapor occupies much volume-the aerobot ascends because it has positive buoyancy, At high altitudes the PCF liquid occupies little volume-the aerobot descends because it has negative buoyancy.

Figure 1 shows a Van't Hoff plot of the atmosphere of Venus and several candidate PCFs. The point at which any PCF line crosses the atmosphere line is the equilibrium altitude for an aerobot employing that particular PCF. When the PCF is above its equilibrium altitude, it is a liquid, and when the PCF is below its equilibrium altitude, it is a vapor. A mixture of water (H_2O) and ammonia (NH_3) has been proposed for use at Venus, where water would boil below 42 km and partially condense above 42 km.[4,5,6] Recently, JPL has developed simple, lightweight means for controlling planetary balloon altitudes through the use of phase-change fluids. A successful campaign of flights in the southern California deserts has demonstrated the feasibility of the PCF balloon concept.[2]

A proposed Venus aerobot mission profile is shown in Figure 2. The alternating evaporation and condensation of the PCF causes oscillatory motion of the system about the equilibrium altitude. Note, however, that the aerobot does not require an on-board energy source to accomplish the vertical motion. Thermodynamically, the aerobot acts as a heat engine using the planet's natural atmospheric temperature gradient below the tropopause to drive the system's vertical motion in the gravitational field. The thermal energy absorbed by the PCF during evaporation at low altitudes is used to propel the aerobot upward. When the energy is released by the PCF during condensation at high altitudes, the aerobot descends, and the thermodynamic cycle is complete.

The natural behavior of the aerobot can be altered by capturing PCF liquid in a small reservoir, thereby preventing its vaporization. In this situation, the aerobot descends to the planet's surface. When the PCF liquid is released from the reservoir it vaporizes again, and the aerobot ascends.

The Venus Environment

The Venusian environment is challenging for both remote sensing from orbit and *in situ* scientific exploration because of its dense, optically thick, and corrosive atmosphere. The nominal flight profile (Figure 2) for a Venus Aerobot could include repeated oscillations between 40 km and 60 km altitude with excursions down to 20 km and possibly even the surface. The near-surface atmosphere of Venus is extremely hot with exceedingly high pressure (eg, 420 ‘C, 67 bar at 5 km). Furthermore, the predominantly $C0_2$ Venusian atmosphere contains ammonia and H_2S0_4 clouds. To study and image the surface, instruments and cameras must be located within 10 km of the surface.’ The extreme variation of environmental conditions between 60 km altitude and the surface imposes severe requirements on all system components.

Venus Aerobot Gondola Requirements

A recent JPL effort has examined low-power camera configurations and thermal control strategies for Venus aerobot operations. The Venus Aerobot Surface Science Imaging System (VASSIS) project began by deriving survivability requirements from the expected aerobot mission profiles and the Venusian environment. Table 1 summarizes preliminary Venus aerobot mission flight requirements, and Table 2 summarizes the Venus atmospheric parameters associated with the flight requirements.

AU components of the aerobot must be able to withstand the environmental conditions listed in Table 2. For example, a thermally and chemically robust balloon material is necessary for the aerobot to survive the sulfuric acid clouds and the extremely high surface temperatures. The focus of this paper, however, is the protective environment for the science instruments (including a camera) in the aerobot gondola. Without such protection” the science instruments will be destroyed by the intense heat and pressure at surface conditions.

It can be shown that each additional kilogram of mass carried on the gondola requires a threefold increase in the overall system mass because the increased balloon volume required to carry the additional gondola mass. Thus, the primary gondola design challenge is to provide thermal protection provide an optical viewport, and allow external data communications with a minimum amount of mass. The following section describes a gondola design that meets the VASSIS requirements.

VASSIS Gondola Design

Pressure Vessels

A schematic of the primary VASSIS gondola temperature control devices is shown in Figure 3. The central spherical instrument housing is 30.5 cm (12 in.) in diameter and is surrounded by a high-temperature multi-layer insulation such as gold foil. The outer pressure vessel is a spherical titanium shell that is 2.5 mm (O. 1 in.) thick. The outer shell is designed to withstand Venus surface conditions of 460°C and 96 bar as well as atmospheric entry force loads of 500 g.[8,9] The central instrument housing is held in place by a series of tension bands (Figure 4) fabricated from braided polybenzoxazole (PBO) fiber material, sheets of which are being considered as the primary Venus balloon material.[10] PBO is known to react with Venus' atmospheric sulfuric **acid**, therefore a PBO balloon skin must be coated with a thin protective material, such as **gold**, to prevent balloon gas leakage.

The cavity between the outer pressure shell and the inner instrument housing is **evacuated**, and various vacuum getter materials are used to prevent contamination due to potential outgassing of materials. The assumed effective radiative **emissivity** between the concentric spherea is 0.01.

Phase-change Material (PCM) and Heat Pipe

A phase **change** material **(PCM)**, $LiNO_3 \cdot 3H_2O$, has been selected to absorb parasitic heat in the lower atmosphere. During descents into the **hot**, lower Venus atmosphere, the PCM will melt slowly at 30 "C. Upon **re-ascent** to the **cool**, upper clouds, the PCM will re-freeze as its heat is transferred to the atmosphere. A simple, hollow stainless steel tube, 1.27 cm (0.5 in.) diameter, **partially** filled with **ammonia**, is the means by which heat is transferred from the central instrument housing to the outer pressure vessel, When the pressure vessel is cooler than the instrument housing, ammonia will condense in the pipe near the pressure vessel wall and will fall by gravity to the inner **instrument** housing. The liquid ammonia will absorb heat **from** the PCM as it boils. The vapor returns to the outer pressure vessel, thus completing a continuous heat transfer **circuit, until** the PCM is **fully re-frozen**.

The heat delivered to the outer pressure vessel by this gravity-fed diode heat pipe (known as a **reflux boiler)** transfers **conductively** through the titanium pressure vessel to an external heat pipe **circuit**, without the necessity of transferring the ammonia itself through the pressure vessel **wall**. This outer, **secondary** heat pipe circuit (Figure 5) is fashioned similarly as a **gravity-fed**, 1.27 cm (0.5 in,) OD hollow tube, wherein ammonia is condensed in an upper finned heat transfer matrix and falls by gravity to the outer pressure vessel wall area where it boils. It may be **necessary** to **gold-**plate all exterior surfaces to inhibit corrosion by the Venus **sulfuric-acid** clouds.

Gondola Thermal Performance

To evaluate the thermal performance of the system, it was **necessary** first to estimate the balloon ascent and descent velocities. A transient thermal model was **constructed** for a 25-kg gondola with a balloon that was fabricated from 0.05-mm (0.002-in.) PBO film. At a maximum altitude of 56 **km**, the balloon is 2.5-m diameter and 25-m long, and it is filled with 50% ammonia and 50 **%** water. The total floating mass of this system is about 100 kg (25 kg **ammonia**, 2S kg water, 25 kg **payload**, 15 kg balloon material, and 10 kg **structure** and miscellaneous). Figure 6 shows the altitude profile for the **aerobot**, and Figure 7 shows the velocity profile for the **aerobot**. (The secondary effects of atmospheric thermal radiation were not included in the simplified **aerobot** trajectory analysis.)

As shown in Figure 7, the initial descent velocity is about 12 m/s, but this slows to about 3 **m/s** near the Venus **surface**. Total descent time required is estimated to be about 3.5 hours, while total ascent time is slightly less than 2.5 hours. These calculations assume a descending coefficient of drag of 0.8 and an ascending coefficient of drag of 0,4, as has been estimated for similar Barth balloon **systems**.[11] Also, **all** balloon water vapor is assumed to be condensed quickly at altitude and boiled quickly near the Venus surface when ascent is initiated.

A thermal model of the **VASSIS** gondola has been constructed and the resulting heat loads are shown in Figure 8 for various altitudes above the Venus surface. Note that extremely low power dissipation rates **(c** 1 W average) are expected for the science instruments during low-altitude operations. The above assumption is reasonable because a **communication** system **would be** used only during upper-atmosphere operation. Thus, no internal electronic power dissipation is shown in Figure 8.

At altitudes below about 10@ the radiation heat leak between the spheres dominates conduction heat leaks from the PBO band supports and the combined conduction and radiation at the camera window (fused silica glass). Total heat load at the surface is about 85 W, Approximately 1.5 kg of PCM mass is **necessary** to absorb the integrated descending heat load (Figure 9), about 1 kg of PCM is required to **absorb** the heat load from 1 hour of surface operations, and about 1 kg of PCM is required to **absorb** the integrated ascending heat load. There is about 0.5 kg of PCM **carried** as margin.

An estimate has been made of the time required for PCM cooling when the balloon bobs between 56 km and 40 km during alternate condensation and boiling of the water in the **water/ammonia** balloon. Approximately two hours of bobbing time (about two **full** round trips) is required for each kilogram of PCM to be **re-frozen. Thus,** one repeatable mission scenario could consist of a 3.5-hour **descent**, 1 hour on the Venus surface, a 2.5-hour **ascent**, and 8 hours bobbing time for a total of 15 hours if about 4 kg of PCM is used. Significantly longer low-atmosphere hover times could be used for hovering at higher altitudes since both the transit time and heat loads are highest for hovers close to the Venus surface.

The total thermal control mass, 7.9 kg, for the VASSIS gondola is shown in Table 3 for the mission scenario detailed above. An additional 5.4 kg is required for the outer titanium pressure vessel, 1.9 kg for the inner instrument housing, and other miscellaneous masses (Table 4) for a total gondola mass of 16.7 kg plus science instruments and communication hardware.

Venus Aerobot Thermal/System Design Tradeoffs

There exist many interesting design tradeoffs between the gondola thermal design and the Venus aerobot balloon system design. First, a tradeoff exists between the enthalpy of fusion (h_{sl}) and the melting temperature of the PCM. Clearly, the larger. the enthalpy of fusion (h_{sl}) of the PCM, the more flexibility in design. Given the same PCM mass, increased h_{sl} provides the capability for prolonged surface operations. If longer surface operations are not required, however, larger PCM heat capacity can be used to reduce gondola mass thereby reducing the size of the balloon required to carry the gondola. Smaller balloons require smaller cruise and entry systems. Thus, the PCM enthalpy of fusion has a significant impact on overall aerobot system design.

An interesting tradeoff exists between the enthalpy of fusion and the melting temperature of the PCM. The lower the PCM melting temperature, the higher the aerobot must fly to refreeze the PCM after surface operations. Higher altitudes require larger (and heavier) balloon systems and therefore heavier cruise and entry systems. On the other hand, higher melting temperatures are advantageous because the system can be smaller and lighter. There is an optimum PCM that will minimize aerobot system mass with its combination of melting temperature and enthalpy of fusion.

Another design tradeoff involves the shape of the balloon and the PCM mass. To limit transit time between the upper, cooler atmosphere and the lower, hotter surface (and therefore reduce the amount of PCM necessary), the balloon should present a small frontal area to the atmosphere. To achieve reduced frontal area, a cylindrical balloon with large aspect ratio (length/diameter) can be used. (The balloon used herein for the gondola design has a rather large aspect ratio of 10.) But, because of high surface area to volume ratios, high aspect ratio cylinders are relatively massive compared to cylinders with near-unity aspect ratios. Balloon shapes with aspect ratios near unity will decrease the mass of the balloon film at the expense of slower descent and ascent rates. A balloon with aspect ratio near unity will reduce balloon mass but require more PCM than a balloon with larger aspect ratio. Thus, a Venus aerobot system design tradeoff exists between balloon mass and PCM mass.

Applications for Outer Planet Exploration

The vacuum dewar, PCM gondola concept has been evaluated for use as a deep-Jupiter descent probe. The Jupiter design, however, does not have a balloon or atmospheric cooling heat exchanger because the mission consists of a single descent only. With an aerodynamic teardrop shaped inconel shell instead of a spherical titanium shell, a 50-kg, 38-cm diameter gondola would take approximately 1.5 hours to descend 414 km from the anticipated Jovian water clouds (5.0 bar, O 'C) to about 500 bar pressure 806 'C, Less than 2 kg of PCM (H_2O) would be required to maintain all science instruments at or below room temperature for the entire descent.

conclusion

This paper shows that a low-mass, thermally protective instrument housing can be developed for Venus aerobot operations. The proposed aerobot mission scenario involves descent to the surface followed by re-ascent to the upper, cooler altitudes of Venus on a 15-hour repeatable cycle. Vacuum dewar technology can be employed to protect science instruments and communication hardware during surface excursions. To prevent temperature increase in the gondola, a phase change material absorbs heat at its melting temperature.

A viable Venus aerobot gondola design which employs 4 kg of phase-change material is serviceable for a mission sequence that includes a 3.5-hour descent to the surface, 1 hour of surface operations, a 2.5-hour ascent to the upper atmosphere (about 50 km), and 8 hours to freeze the phase-change material. Total aerobot mass is 95 kg. The gondola mass is 25 kg with 8.3 kg available for science instruments and communication hardware.

The basic configuration of outer pressure vessel, inner evacuated MLI region, and inner science vessel with PCM has potential uses for deep atmospheric studies of not only Venus but for Jupiter and the other, somewhat cooler, gas giant planets of Saturn, Uranus, and Neptune.

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Table 1. Venus **aerobot** mission flight requirements.

Parameter	**Requirement**
Mission duration	30-90 days
Maximum atmospheric entry deceleration	**250–500** g
Estimated **descent, ascent,** and float periods	Descent: 7 **hr,** Ascent: 4.5 hr, Float: o-2 **hr**
Flight altitude	**surface < z < 60 km**

Table 2. **Venusian** environment **parameters** corresponding to flight requirements.

Parameter	value
Atmospheric temperature range	-10 “C< T **< 470** “C
Atmospheric pressure range	**0.2 bar < P < 100 bar**
Atmospheric corrosives	Sulfuric acid
solar flux	40 **W/m²** (diurnal average)
Length of day as seen by **aerobot**	- **96** hours
Length of night as seen by **aerobot**	~ **96** hours

Table 3. **VASSIS** temperature control mass summary.

Component	Mass **(kg)**
Phase-change Material **(PCM)**	4.0
PCM Heat Exchanger (Inside Gondola)	**1.5**
MLI (Gold Foil)	1.0
Internal Gravity-fed Heat Pipes	0.3
External Heat Exchanger **(Beryllium** Fins)	0.9
Getters	0.2
Total	7.9

Table 4. **VASSIS** gondola mass **summary**.

Component	Mass **(kg)**
Temperature Control	7.9
Outer Titanium Shell	5.4
Inner Titanium Shell	1.9
Tension-band Supports	0.5
Miscellaneous	1.0
Science **Instruments** and Communication	8.3
Totat	25.0

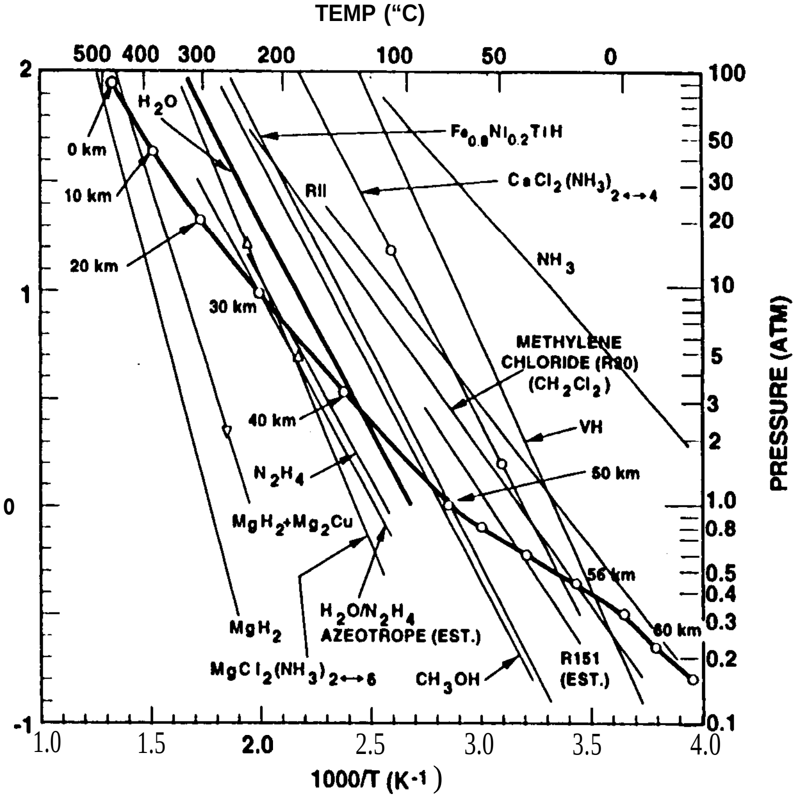

Figure 1. Van’t Hoff plot for Venus atmosphere and candidate PCFs.

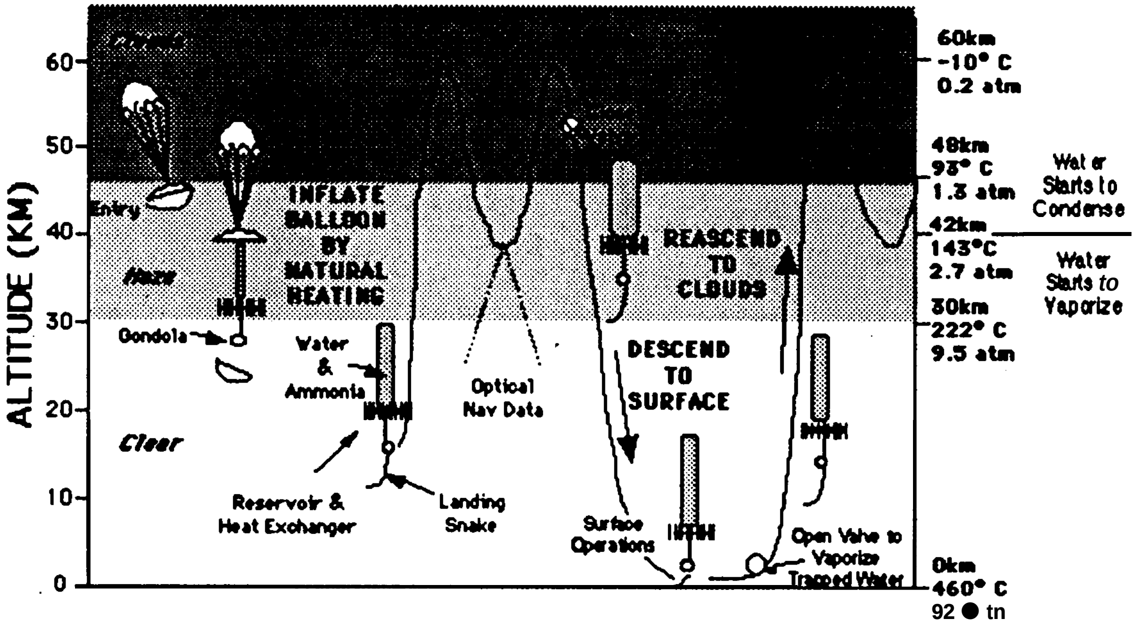

Figure 2. Venus aerobot mission profile with surface descent capabilities.

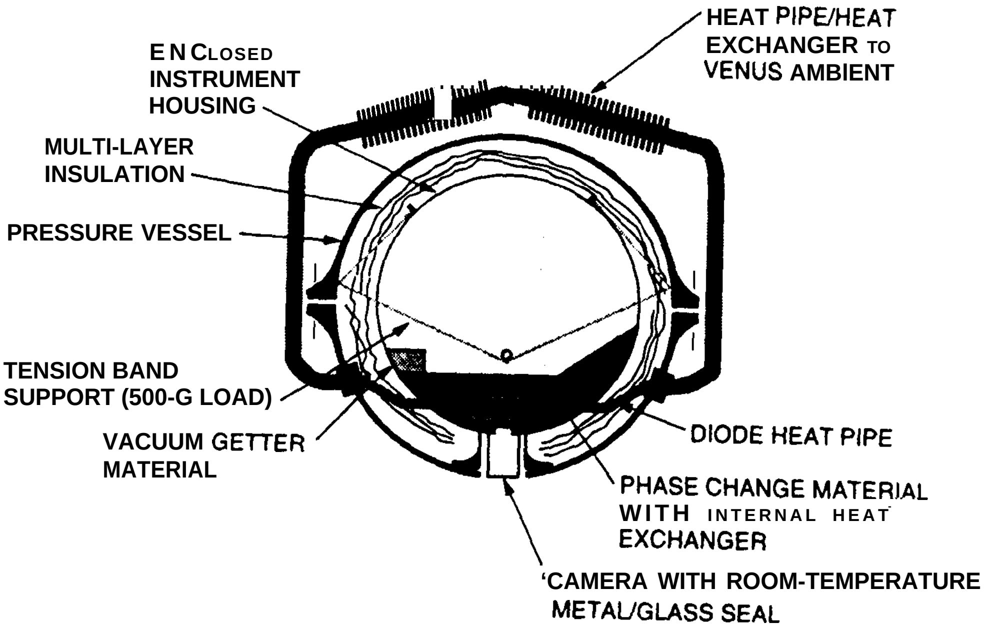

Figure 3. VASSIS gondola temperature control schematic.

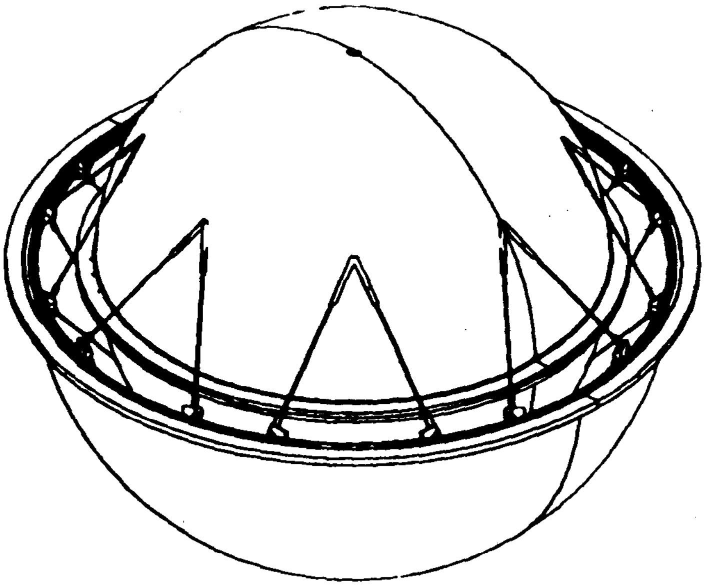

Figure 4. PBO Tension-band support system.

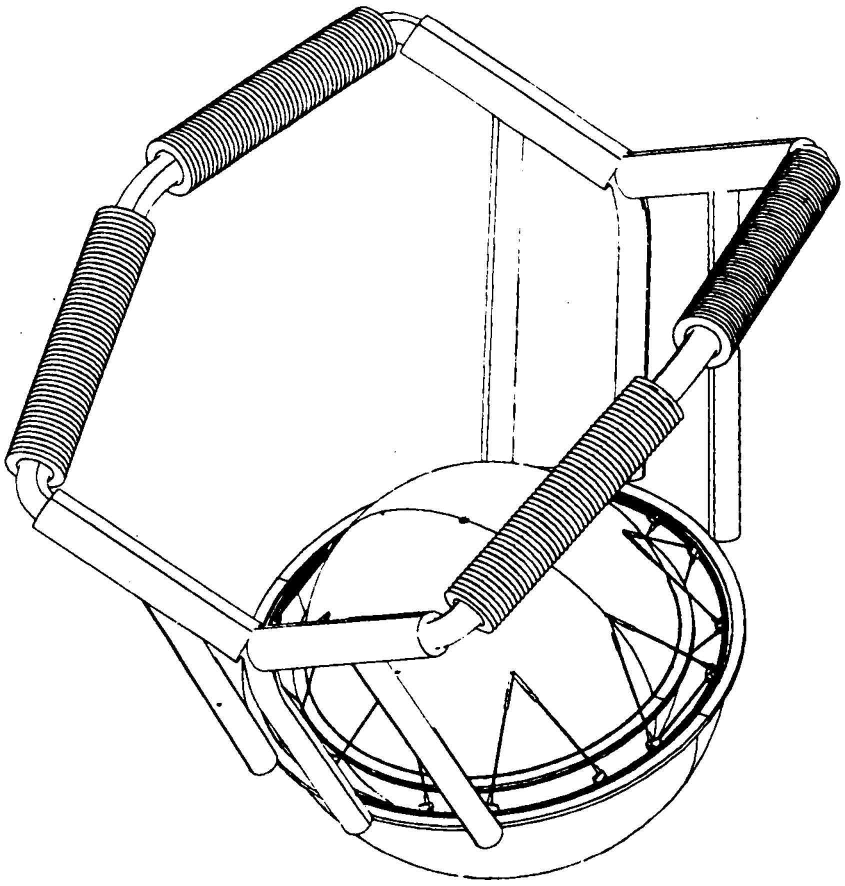

Figure 5. Heat exchanger configuration.

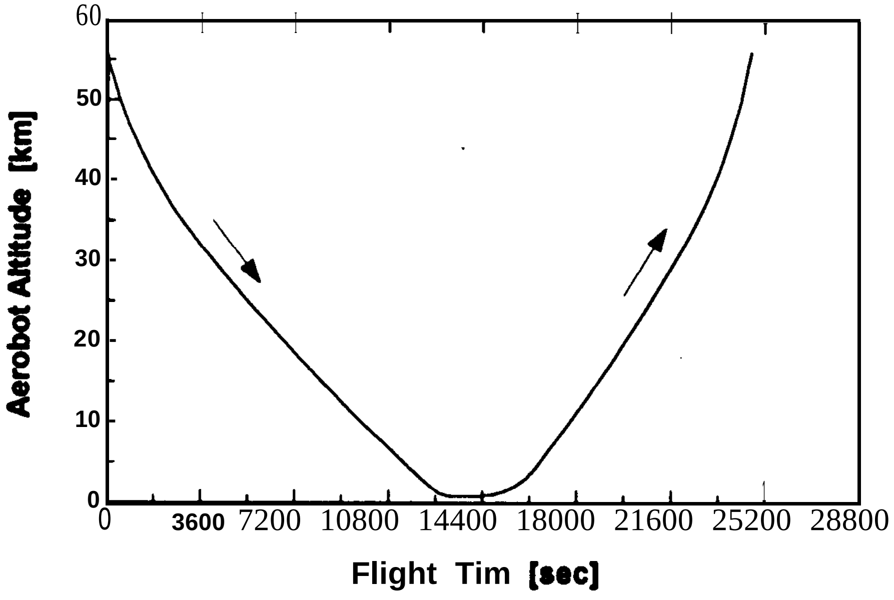

Figure 6. Aerobot altitude profile.

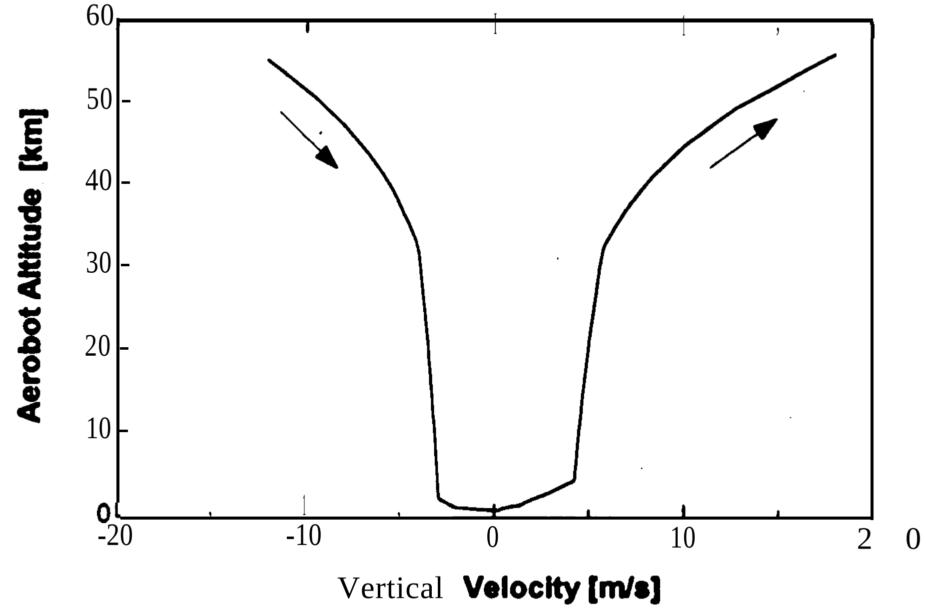

Figure 7. Aerobot descent velocity profile.

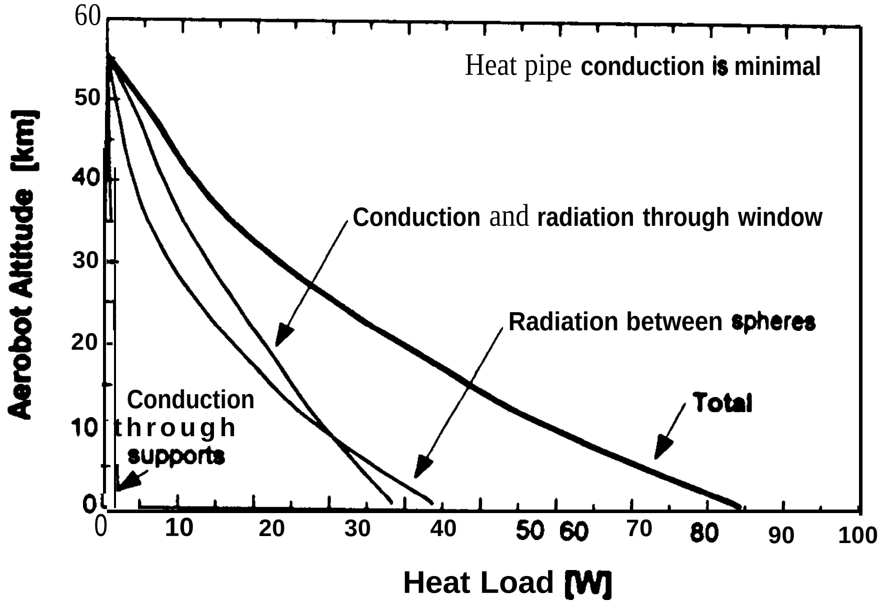

Figure 8. VASSIS gondola heat loads.

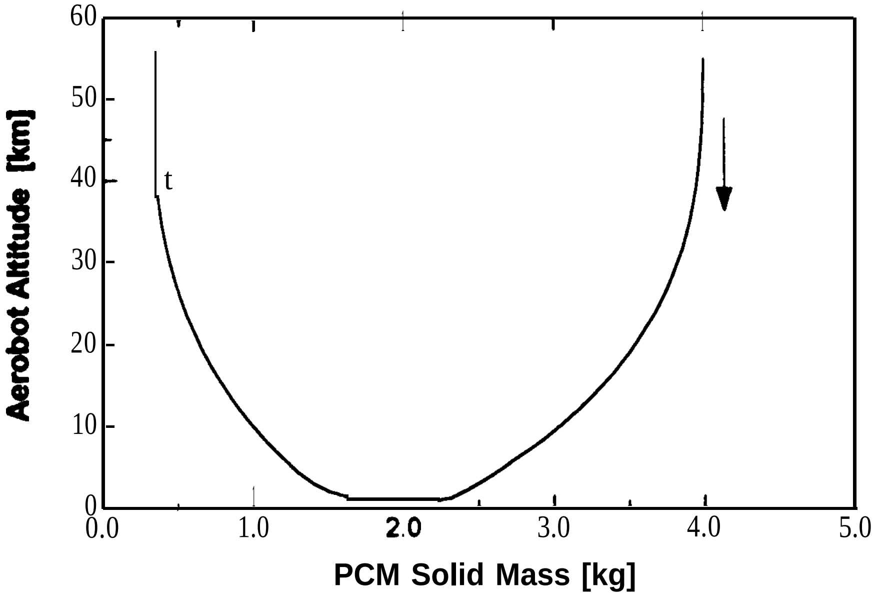

Figure 9. PCM solid mass during flight.