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VENUS GEOSCIENCE AEROBOT STUDY (VEGAS)

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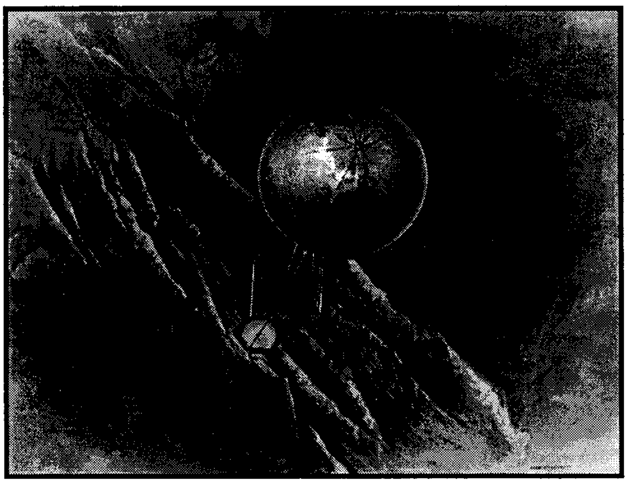

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Abstract

The Venus Geoscience Aerobot Mission Study (VEGAS) was a four-month analysis of a semi-autonomous, altitude-controlled balloon mission to Venus. The study focuses on a Delta launch in the 2007 timeframe, with a nominal 100-day balloon mission and orbiter telecom relay. After the initial balloon and payload deployment in the Venusian atmosphere, the balloon is capable of repeated excursions from altitudes of 60 km to the surface. Active control of altitude is achieved using a "phase change fluid" buoyancy control, whereby the planet's lapse rate is used to periodically condense, trap, and boil a "phase change liquid". Limited horizontal mobility is achieved by using real-time wind pattern predictions. The mean circumnavigation time of seven days and the extensive altitude coverage affords unique science objectives including long-duration passive atmospheric measurements, atmospheric/surface interactions and cycling, global high-resolution near-surface imagery, and remote surface mineralogy and geology. Key technologies required are addressed including thermal control, high temperature balloon envelopes, power generation, and autonomous state determination (navigation and control).

Overview: Mission Study Scope, Constraints, and Assumptions

VEGAS is a preliminary study to develop a Venus Aerobot surface and atmosphere mission concept. Preliminary system design definition includes: strawman science payload, key technical issues, high level requirements, mission and system options, rough cost estimates, and technology needs. Primary mission constraints are: 2007 Venus opportunity, Delta class launch vehicle, pioneer Venus entry design with SOA technology, and moderate class mission cost.

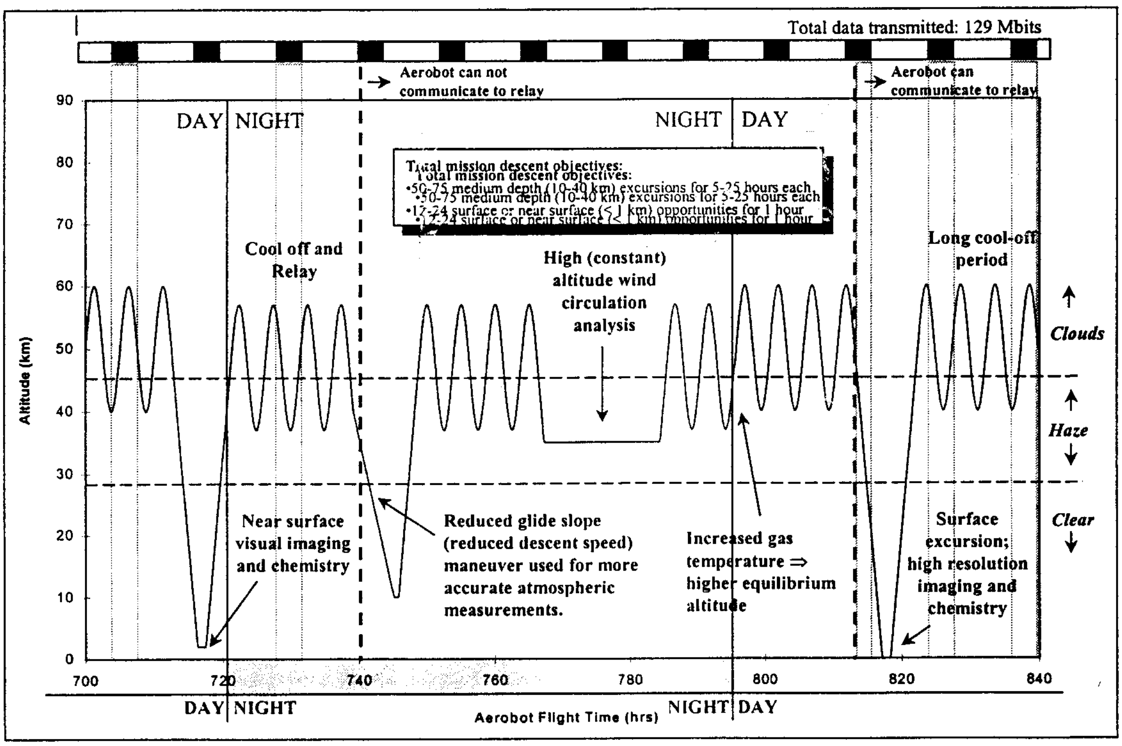


Figure 1: Nominal VEGAS mid-mission profile.

Primary mission assumptions are: zero-pressure balloon with phase-change fluid altitude control, orbiter data relay to earth, 30 kg balloon gondola including science payload, room temperature electronics compartment, and greater than 100 day mission lifetime. The entry probe is delivered by a ComSat, which enters into a 12-hour elliptical orbit. The Aerobot payload deploys in the atmosphere and orbits Venus every 7-8 days at approximately 50 km. The baseline mission plans for on average two descents per Aerobot sol (7 to 8 days). The balloon ascends to high altitude to cool, receive solar power, and communicate. The gondola houses an electronics pressure/temperature vessel capable of maintaining "room-temperature" (< 30°C) electronics for up to 2 hours in a 100-bar, 480°C near-surface Venus environment. An overview of the mid-mission baseline profile is shown in Figure 1.

Environment

Initial entry into the Venusian atmosphere induces a 200-g to 500-g peak deceleration (dependent on entry angle). During the baselined bottom-inflation deployment, a shock absorber (such as ripstitch) is required to mitigate the high loads on the extended balloon envelope (3-g to 6-g load). Once inflation begins, primary environmental constraints include: wind shear in a high-density environment, balloon stability, and parachute/balloon separation (to prevent tangling).

During the operational (deployed) phase of the mission, key environmental issues include sulfuric acid droplets in clouds, optically thick atmosphere, and a range from peak altitude conditions of −20°C at 0.2 bar to surface conditions of 460°C at 92 bar. The Venus sulfuric acid droplet diameter and number density are given in Figure 2 and Figure 3. Droplets range from 0.2 μm at lower altitudes to 8 μm in diameter in the upper haze; number densities range from 10 N/cm^3 to over 1000 N/cm^3 in the upper cloud region. Heating of the gondola at various altitudes, due to both direct and scattered solar heating (from above and below the gondola), is shown in Figure 4. Thermal system and pressure chamber design is based on these estimated heating rates and the temperature and pressure profiles provided in Figures 5 & 6. Nominal mission altitude and position predictions are based on the wind models provided in Figure 7. VEGA 1 & 2 measured meridional winds at 2.5 m/s (towards the equator). Maximum downdrafts expected are 3 m/s, with an average of 1.5 m/s. Turbulence is expected less than 0.6 m/s RMS variation.

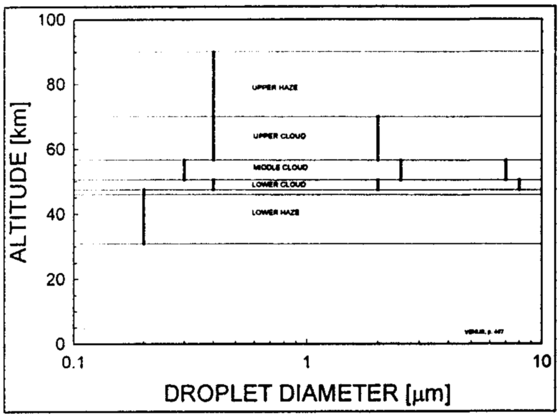


Figure 2: Sulfuric acid droplet diameter for various atmospheric regions on Venus.

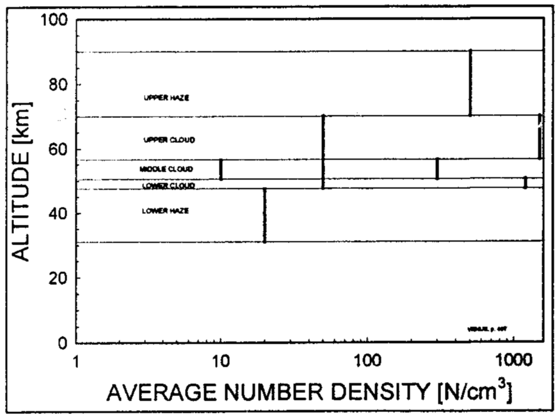


Figure 3: Sulfuric acid droplet abundance for atmospheric regions on Venus.

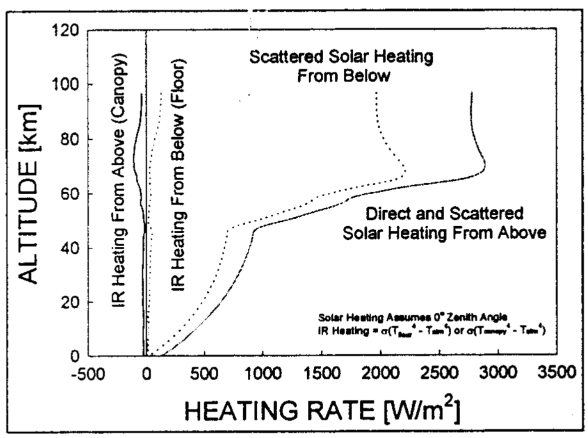


Figure 4: Solar heating from both direct and scattered sources (from below and above gondola).

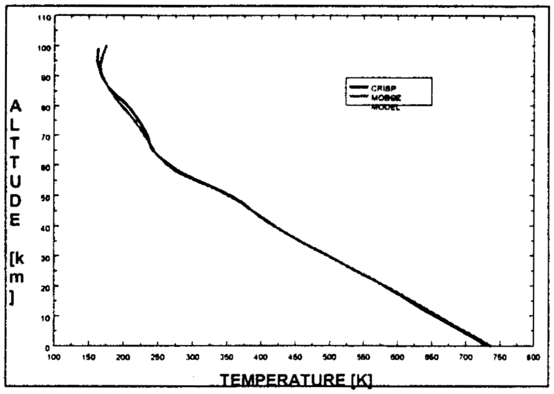


Figure 5: Temperature profile of the Venus atmosphere.

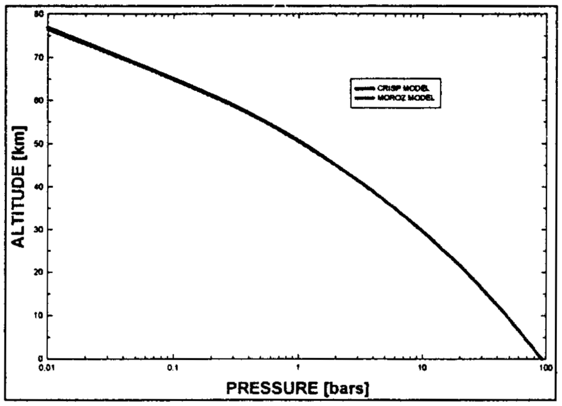


Figure 6: Pressure profile of theVenus atmosphere.

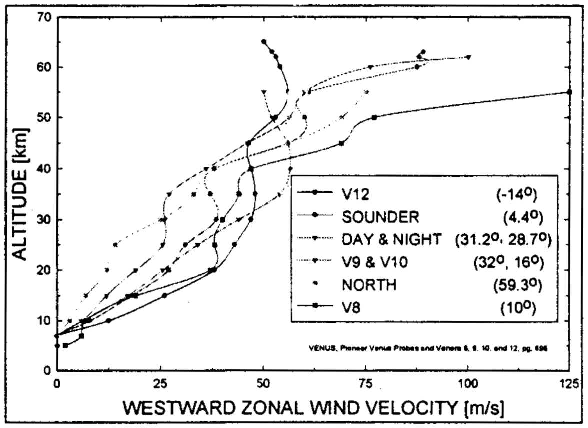


Figure 7: Westward zonal wind velocity.

Buoyancy System

The buoyancy system includes the balloon envelope, phase-change fluid, support valves, and evaporator (Figure 8). The primary balloon envelope material requirements include deployment from a small package while hanging from a parachute at 0.5 bar to 5 bar pressures and 10°C to 170°C temperatures. The balloon must survive compact storage at temperatures as low as 5°C (during cruise). Heating the balloon during cruise was left as an option. While maintaining chemical and physical properties, the envelope should withstand periodic short (less than two-hour duration) excursions to the surface for at least 100 days; this includes frequent exposure to sulfuric acid. Other requirements include low permeability of the phase-change liquid/gases and lifting gases, and acceptable pinhole seaming fabrication and folding of the envelope. Minimum tensile strength of 450-psi is required, based on a 1-mil thickness, 3-m balloon diameter, and a 25-kg gondola.

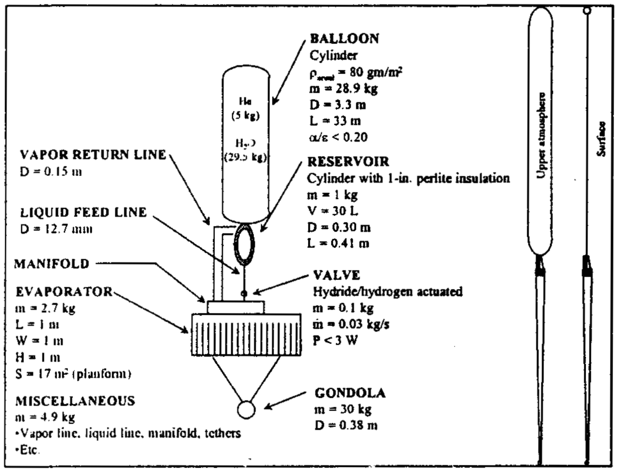


Figure 8: Buoyancy system configuration.

Balloon Envelope

Figure 9 outlines the six primary balloon envelope options. There are four functional roles for the materials: (1) gas barrier, (2) strength member, (3) environmental compatibility, and (4) thermal/optical coatings. PBO film (85 ksi, 7 Msi) seaming is done with PBO fiber (840 ksi, 40 Msi) or carbon fiber (600 ksi, 35 Msi) stitching using high temperature adhesives for sealing. PIBO film can be seamed with high temperature adhesives or PIBO solvent adhesives (does not require sealing). The PIBO composite option is combined with PBO or carbon fiber scrim, using PBO or carbon fiber stitching and PIBO solvent adhesive seaming. The PFA film composite is stitched in the same way, but sealed with PFA adhesives. Sulfuric acid protection (noble metals), optical coating (vapor-deposited oxide), and phase-change fluid protection (noble metals) are required for all but the PFA option.

Most envelope options, including PBO fiber fabric/scrim in PTFE coating or metal foils, are less appealing due to high temperature sealant breakdown and material degradation. In fact, only option 1 (PBO film with PBO stitching) is considered suitable for greater than three surface descents. For less demanding missions (less than three descents or multiple descents to 10-km), options 1-6 are suitable. Key technological hurdles are low α/ε coatings, deposition/composite technology, high temperature sealants, balloon fabrication techniques, and film manufacturing/scaling.

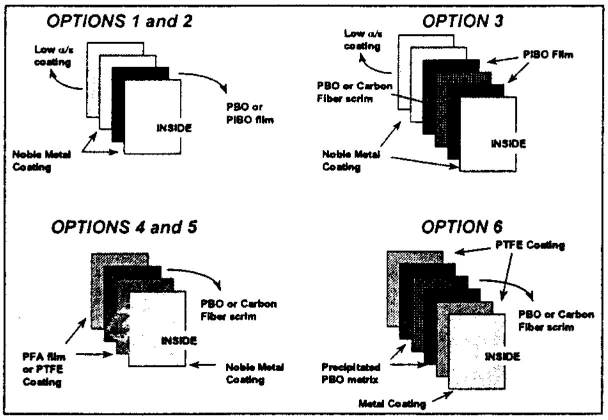


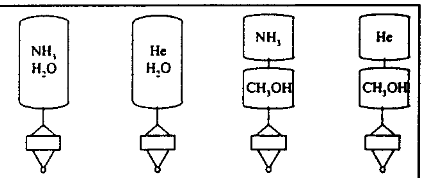
Figure 9: The six primary multi-layer balloon envelope options explored in VEGAS.

Phase-Change Fluid (PCF)

Phase-change controlled balloons act as a heat engine; energy is absorbed from the lower atmosphere and rejected to the upper atmosphere. ALICE and BARBE, two JPL phase-change test programs, have practically demonstrated and validated this concept. Using a typical PCF system, altitude control is achieved by the following sequence:

- Trap the condensed PCF liquid as ascending in cruise phase (valve close)
- Allow the system to descend after condensation complete
- Initiate a hover sequence by partially releasing and boiling the fluid (valve open, valve close)
- Hover for a limited time (dependent on altitude)
- Initiate an ascent by releasing the remainder of the liquid (valve open).

Three different phase-change system configurations are investigated: (1) single-balloon (pure-fluid) for water and methanol, (2) single-balloon (mixture systems) for helium/water and ammonia-water, and (3) dual-balloon systems for ammonia-methanol and helium-methanol. All phase change states are considered: condensation, evaporation, boiling, solidification, and sublimation. Specific factors addressed are maximum altitude, thermal lag in mixture, effect of completeness of gas mixing on condensation, and importance of solar energy absorption by the balloon skin. Figure 10 below outlines the four primary options, (1) ammonia/water mixture, (2) helium/water mixture, (3) dual-balloon ammonia/methanol, and (4) dual-balloon helium-methanol.



Peak altitude [km]	60	60	60	60
Lowest altitude [km]	0	0	0	0
Boiling altitude [km]	42	42	52	52
Gondola mass [kg]	25	25	25	25
Balloon system dry mass [kg]	39	30	42	31
Lifting gas mass [kg]	37	5	47	6
PCF mass [kg]	25	25	25	25
Total floating mass [kg]	126	85	139	87
Balloon diameter [m]	3.2	3.2	3.2	3.2
Buoyancy control margin [%]	48	72	25	40

Figure 10: Comparison of PCF options.

The two most promising options are the ammonia-water mixture and helium-water mixture, both having a cruise altitude range during the day of 34-km to 62-km, and during the night of 33-km to 61-km. Various mixture ratio profiles for the baseline helium-water design are shown in Figure 11.

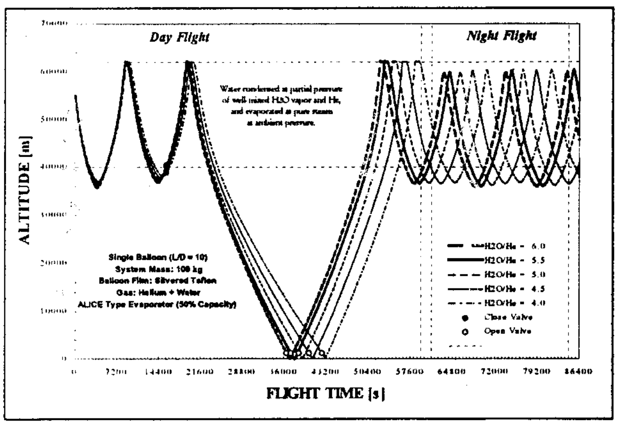


Figure 11: Effect of mixture ratio for the baseline helium/water mixture.

Both mixture options meet requirements for altitude variation, payload fraction, and solar heating (α/ε<0.21). The small difference in molecular weight between the ammonia-water mixture gases may be beneficial to mixing problems. The helium-water mixture offers a lighter gas and provides higher buoyancy control margin. Likewise, the helium-water mixture offers a compact, low-mass system. Both options require better evaporator performance to increase altitudes and decrease high temperatures. The baseline performance expected from the helium-water phase-change fluid is as follows:

- 6-8 hours for each near-surface descent (up to one hour at the surface)
- 2-3 near-surface descents for every 8 earth days
- Cruise altitude cycling once every four hours.

PCF System (Valve, Evaporator, Reservoir)

Five PCF valve options are investigated: a single, normally open hydride-hydrogen actuated valve, two hydride-hydrogen actuated valves (one normally open, one normally closed), a magnetic latching valve, tube pincher, and a tube lifter. For the single-valve option, flow rate is proportional to the distance below the reservoir. The hydride-hydrogen single-valve weighs below 100-g. It would normally close at temperatures less than 30°C and require less than 3W to keep closed. The two-valve system (shown in Figure 12) would have advantages of minimal power required for control, reduced valve actuation time, system redundancy, and simpler valves (probably no vacuum jacket required around valve). Disadvantages of the two-valve option are system complexity and additional mass.

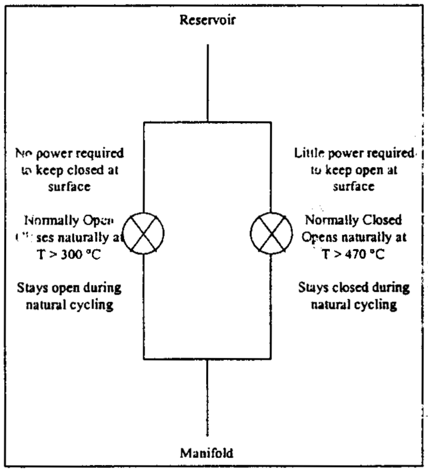


Figure 12: Dual-valve system diagram.

The evaporator is designed to provide descents no lower than 30-km on natural cycling – an approximate surface area of 34 m^2. Construction approach (i.e short verticle dimension) is such as to survive water hydrostatic pressure (prevent de-lamination). Earth tests have shown violent boiling, causing large pressure spikes in evaporator tubes. The evaporator options are shown below in Figure 13. The baseline option is the accordian design, which requires minimal liquid head in the evaporator tubes and provides the simplest deployment configuration. The material would be constructed with a double layer of the same material used for the balloon envelope (with a low α/ε coating). Sewn or sealed tubes are constructed from the two layers of material. Spacer springs will allow expansion of the evaporator tubes and will provide air flow for convective heat transfer.

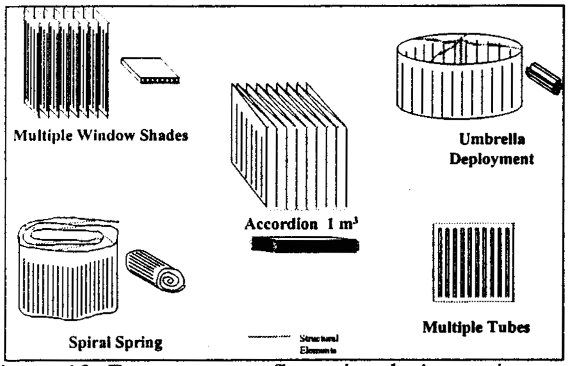


Figure 13: Evaporator configuration design options.

The reservoir is designed such as to limit heat loss to less than 1000 W (to water at the Venusian surface). This provides greater than a one-hour dwell time. The high thermal capacitance of water makes this an easy problem. The reservoir must also provide a volume of 30-L for condensed water. The baseline design is cylindrical, with a diameter of 0.3-m and a length of 0.4-m. The pressure of the chamber must maintain equilibrium with the local atmosphere, while preventing heat leak into the reservoir. Insulation, such as 0.02-m thick perlite, will provide thermal mass to delay this liquid heating.

Liquid and vapor lines between the reservoir, balloon, and evaporator must provide a liquid flow rate of 30-gm/sec, a vapor flow rate (evaporator-balloon) of 2-m/s (at 42-km), and must be designed such as to not be a load-bearing member of the flight train. The liquid line is from 9.5-mm to 12.7-mm diameter, the vapor line is less than 15.2-cm in diameter, and both lines are built from the same material used for the balloon envelope. The tethers between the balloon, evaporator, and reservoir are designed to support a 35-kg gondola, 10-m free fall, with a 1-m deceleration height (SF=10). Baseline design is a 2.5-m diameter PBO tether (tensile strength 5.8 GPa), weighing under 1-kg.

Buoyancy System Performance

Multiple modeling approaches are taken in the VEGAS study. For buoyancy system modeling, two methods are used: bottom-up mass modeling (item-by-item accounting) and top-down mass modeling (mass ratios from previous systems – e.g. VEGA). For PCF vertical motion, a dynamic trajectory model incorporates full

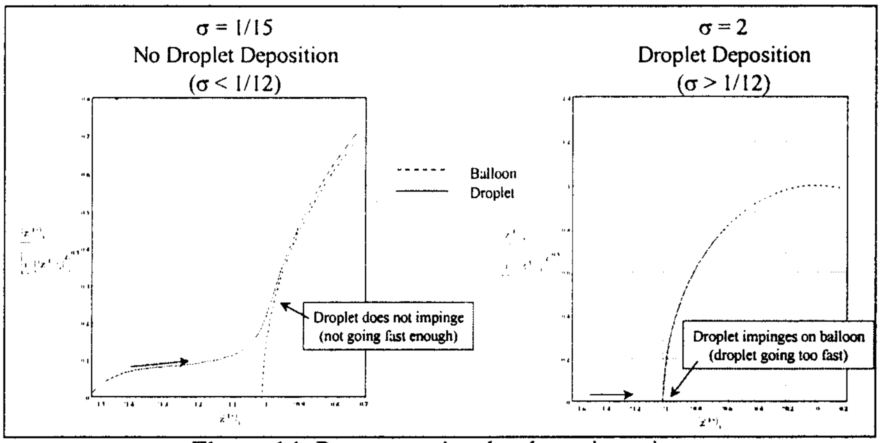


Figure 14: Representative droplet trajectories.

dynamics and thermodynamics of the motion including mixed gas condensation, droplet deposition, balloon shape, and component sizes. A simplified descent model was also used to test form drag and skin friction on balloon shapes and to provide a backup "sanity" check on the dynamic modeling.

Three approaches are used for sulfuric acid droplet depositions: a simple integral model (all cloud droplets deposit on balloon), a complex fluid dynamic model (droplet trajectories based on inertia and drag), and mass retention experiments performed at JPL (evaluates acid retention properties of candidate materials). Although the simple droplet model showed significant problems for the 47.5-km to 50.5-km range (23 $g/m^2/km$), the dynamic model and experimental indicate less retention of droplets. The results of the lab experiments show that enough mass is retained to alter the flight trajectory. 40 g/m^2 of sulfuric acid can be retained by an Al foil surface (2-mil PBO has pareal=80 gm/m^2); 39-g/m^2 of sulfuric acid can be retained by a teflon surface; 40 g/m^2 of water can be retained by an Al foil surface. The baseline balloon system (balloon material at 80-g/m^2) has enough ΔB to continue cycling under this full load. Based the dyamic model and a fineness ratio (L/D) of 10, the system spends only slightly more time for near-surface excursions than a fineness ratio of 3 (see Figure 15).

The dynamic model in Figure 14 shows that there is no expected droplet deposition for an $\alpha<1/12$ (ratio of time required to accelerate particle to gas velocity to time taken by flow to move one radius of the particle). To get a deposition of $\alpha < 1/12$, it would require a droplet diameter greater than 100-μm (the worst case expected is 10-μm) and a balloon diameter less than 0.01-m (actual design is 3-m). The practical geometry (sharp edges, seams, etc) of the balloon may induce higher than expected droplet deposition.

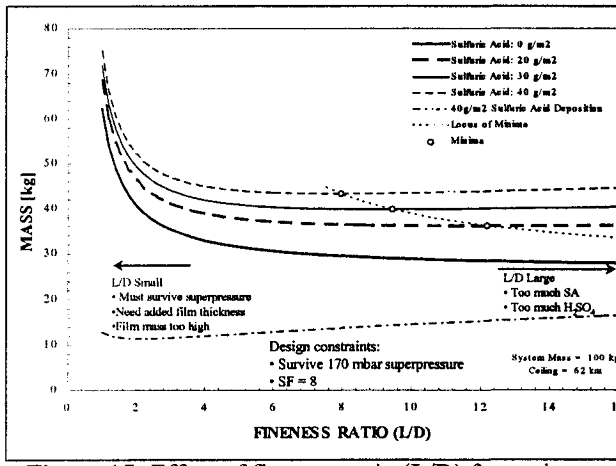


Figure 15: Effect of fineness ratio (L/D) for various sulfuric acid droplet density values.

Buoyancy - Conclusions

To date, all of JPL's earth-based PCF Aerobots have used pure-fluid buoyancy control systems such as pure R114 or azeotropic R124/R142b. Questions exist about the behavior of highly-zeotropic mixtures like helium and water. There is a need to fly a zeotropic mixture PCF system at Earth to demonstrate the concept. Specific recommendation is a 95% helium, 5% methanol vapor mixture to test condensation only. Maximum expected altitude would be 10-km.

The buoyancy system lifetime will be limited by a number of components and factors. Included is the corrosion of unprotected balloon skin, degradation of the balloon skin due to thermal cycling and high-temperature exposure, and buoyant gas leakage. High temperature descents will increase permeability of the balloon film and increase leakage. Base leakage rates will be on the order of 100-g per descent. Metalization of the balloon film reduces the leak rate significantly.

Several additional studies need to be performed on droplet deposition for sulfuric acid. Issues that need addressing include droplet effect on other components, balloon seams, and system performance. PCF control approach and control fidelity require further detailed study. The following figures show relevant data to both baseline and optional buoyancy system designs.

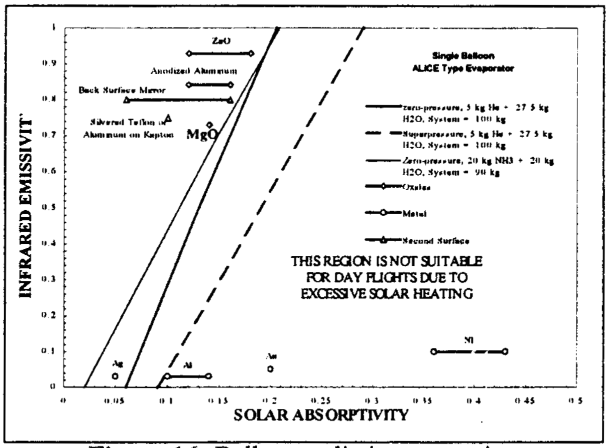


Figure 16: Balloon radiative properties.

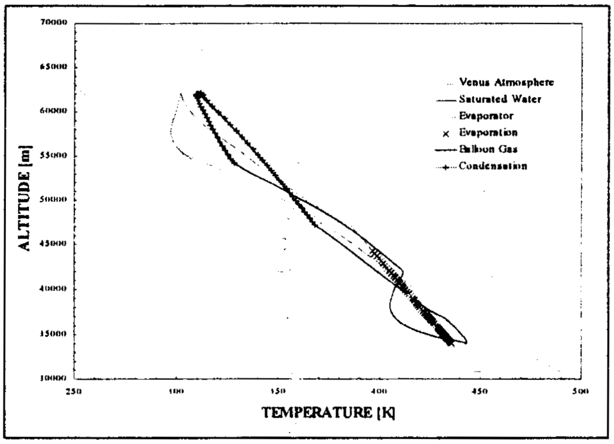


Figure 17: PCF Evaporation and Condensation Physics

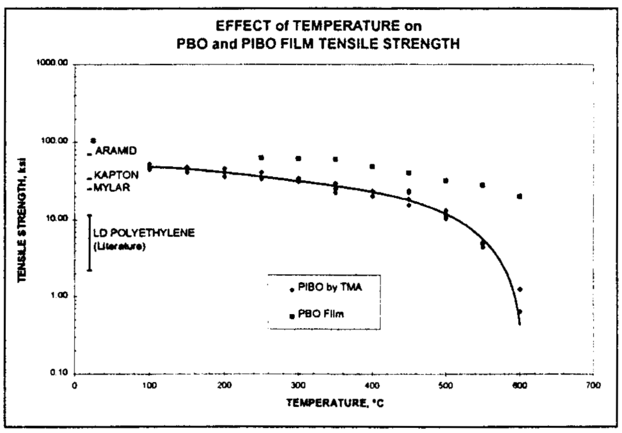


Figure 18: Temp vs. PBO/PIBO tensile strength.

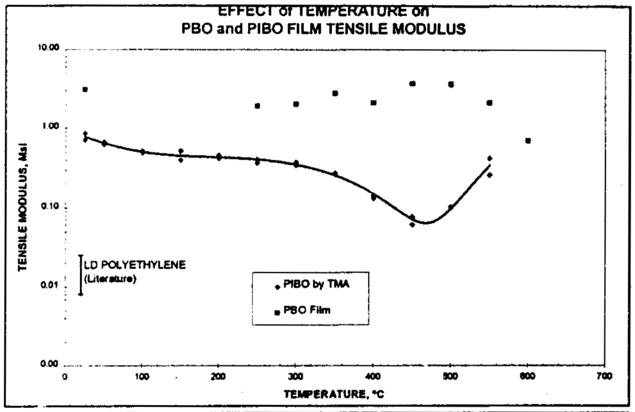


Figure 19: Temp vs. PBO/PIBO tensile modulus.

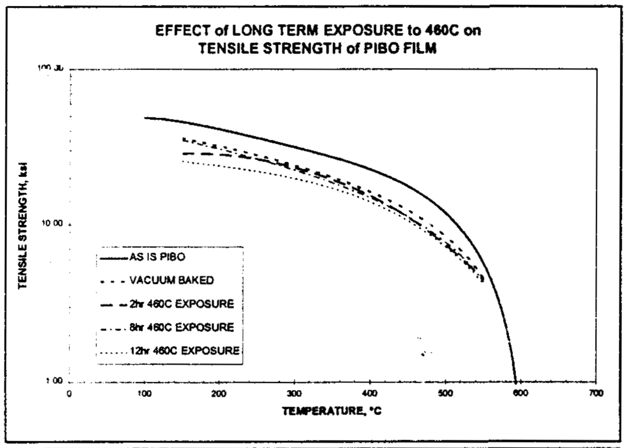


Figure 20: Long term exposure to 460C, PIBO film.

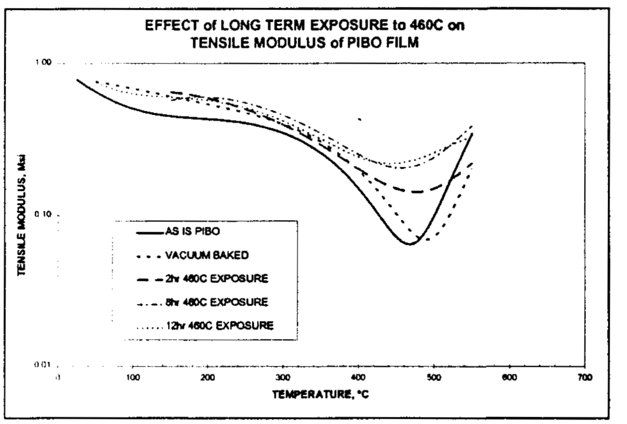


Figure 21: Long term exposure to 460C, PIBO film.

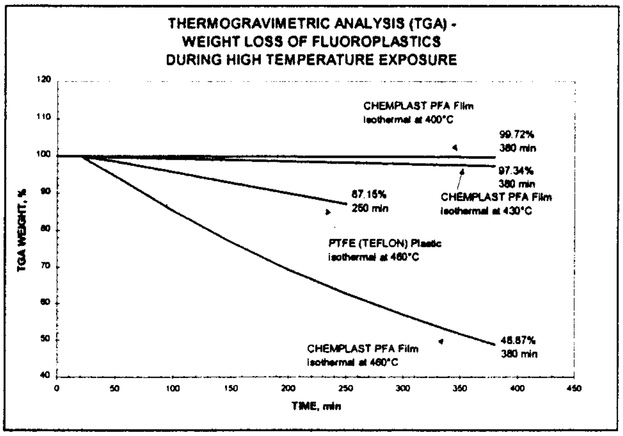


Figure 22: Thermogravimetric analysis of fluoroplastics during high temperature exposure.

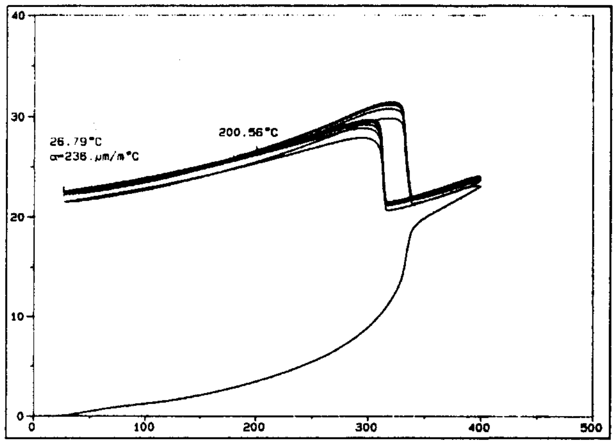


Figure 25: Temperature cycling of PFA.

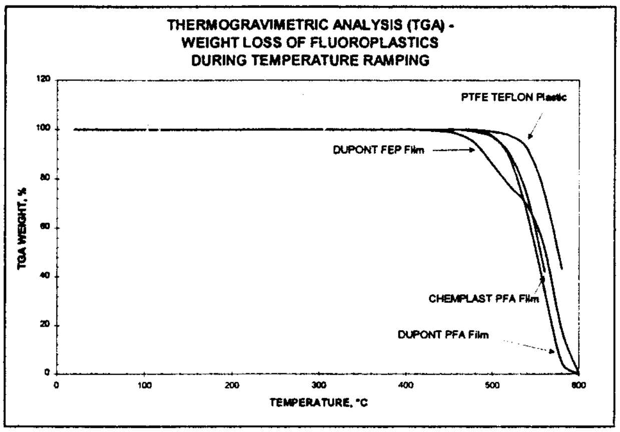


Figure 23: Thermogravimetric analysis of fluoroplastics during temperature ramping.

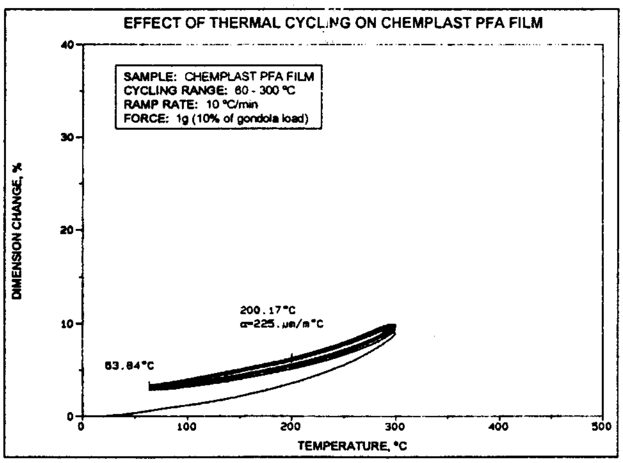


Figure 24: Effect of thermal cycling on chemplast PFA film.

Entry, Deployment, and Inflation Systems

The entry and deployment analysis addresses component storage and packing, deployment sequencing, and inflation stability. A protective aeroshell is used for atmospheric entry and aerial deployment. Components necessary for the deployment include pyrotechnic and parachutes for extraction, storage tanks and inflation plumbing for helium and water, and internal support structures for the balloon, gondola, evaporator, and fluid storage tanks. The target mass of the support cruise and entry system is less than 40% of the system mass. The inflation system is intended to fully inflate and detach from the balloon before reaching a 30-km altitude. Specific concerns include: spinnakering or balloon instability, low subsonic gas inflation velocities (to avoid causing damage to the balloon), midair collision of balloon and jetisoned parts, isolation of pyro firings, tangles, and excessive deployment loads.

Deployment Sequence

The VEGAS entry sequence is shown in Figure 26. The probe enters at 11,200 m/s, deploys a drogue chute to slow to 28 m/s by 45-km, and then deploys the main chute to slow to 10 m/s. The balloon is now inflated from the bottom with first water, then helium. The parachute is released after inflation is complete, followed immediately by the inflation system (and aeroshell) cutaway. Sizing to a maximum 300-g deceleration on entry (over a time span of 10 seconds), the estimated entry angle is 35 degrees.

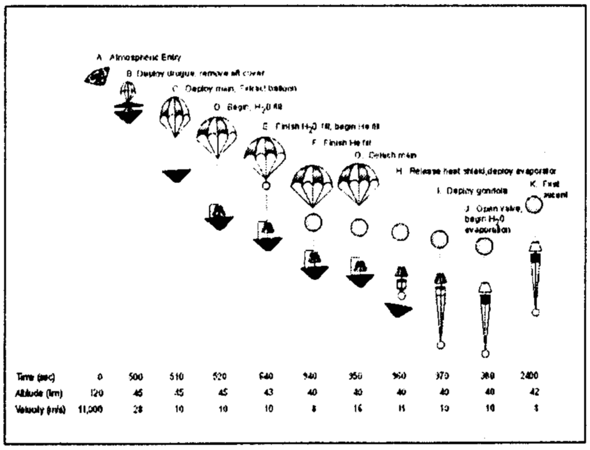


Figure 26: Entry sequence.

Based on the sequence requirements, the deployment dictates a stacking order and spatial relationships. The aeroshell stability requires a low center of gravity and high center of pressure, with the center of gravity along the centerline. The aeroshell size is primarily driven by the balloon volume of 0.56 m^3. In configuring the system for packing options, it is assumed that existing P-V aeroshell technology (flight-qualified shapes and materials) is used. Heavy components (gondola, tanks, and balloon) are directly tied to the aeroshell forebody. Triangular placement of heavy components around the apex balances the center of gravity. Packing options include a 100%, 120%, and 150% of P-V large (see Figure 27).

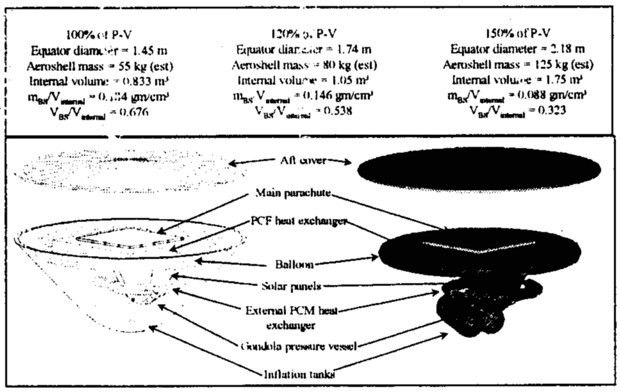


Figure 27: Packing options and diagram.

Inflation System

The baseline inflation design is a bottom, sequencial fill. Helium is the pressurant, and pushes the water into the reservoir. The heat shield is jettisoned and gondola deployed after the balloon is filled to minimize the fill-tube length. Fill rates will be on the order of 2 minutes for water (230-g/s, u=0.48 m/s) and 5 minutes for helium (17 g/s, u=140 m/s). Stability of the balloon is a concern, with side loads on the inflating balloon threatening to tangle the parachute and balloon. The proposed solution is to maintain a small and bounded angle (off vertical) for stability. Static stability is not difficult to achieve for Venus because of small descent velocities (< 10-m/s) and lightweight parachutes (1.5 kg).

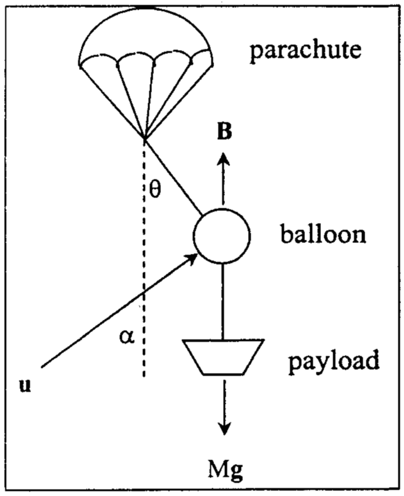


Figure 28: Deployment static stability diagram.

As shown in Figure 29, the VEGAS (VGA) ballistic coefficient is low compared to Vega, Galileo, and PV. This is due to several low-density components. VEGAS deceleration system mass (M_{DS}) is comparable to previous missions based on its fraction of the total entry mass (M_T). PV had a high-density payload allowing a smaller aeroshell.

Spacecraft	Planet	Total Entry Mass (kg)	Heat Shield Area (m^2)	Heat Shield Geometry	M_T/A_{hs}	M_{DS}/M_T
VGA	Venus	243	2.37	90 deg cone	102.5	0.34
VEGA	Venus	1720	4.52	sphere	380.5	1.00
Pioneer-Venus (L)	Venus	316	1.65	90 deg cone	191.5	0.25
MABS	Mars	340	4.52	140 deg cone	75.2	0.52
Pathfinder	Mars	570	5.51	140 deg cone	103.4	0.37
Galileo	Jupiter	331	1.22	90 deg cone	271.3	0.64

Figure 29: Comparison of missions and studies.

Future work on the entry and deployment system should include the development of lighter-weight aeroshells (largest potential mass savings). Also required is analysis and testing of both balloon skin flutter and spinnaker phenomena. The study also shows a need for investigating staged-deployment strategies and technology (reefing sleeves, shock load absorbers). Also, the study suggests scaled tests of prototype entry & deployment hardware.

Gondola

The gondola system is composed of the science payload, structure, thermal control, communications, avionics, and power. High-level gondola requirements include a low-power low-mass electronics stack, DSN tracking and navigation (with greater than 30Mbit/day data return), less than 500-g entry loads, sulfuric acid exposure, and autonomous position determination to within 100-km.

Figure 30 shows a conceptual view of the baseline gondola. The spherical pressure vessel can withstand pressures up to 100 bar and temperatures up to 460°C (for up to one continuous hour). Also shown is functional diagram of electronic system components.

CATEGORY	INT MASS	EXT MASS	TOTAL MASS
Science	2.1	2.1	4.2
Communications	1.1	0.9	2.0
Avionics	2.1	0	2.1
Power	2.0	1.0	3.0
Structure/Thermal	19.9	0.9	20.8

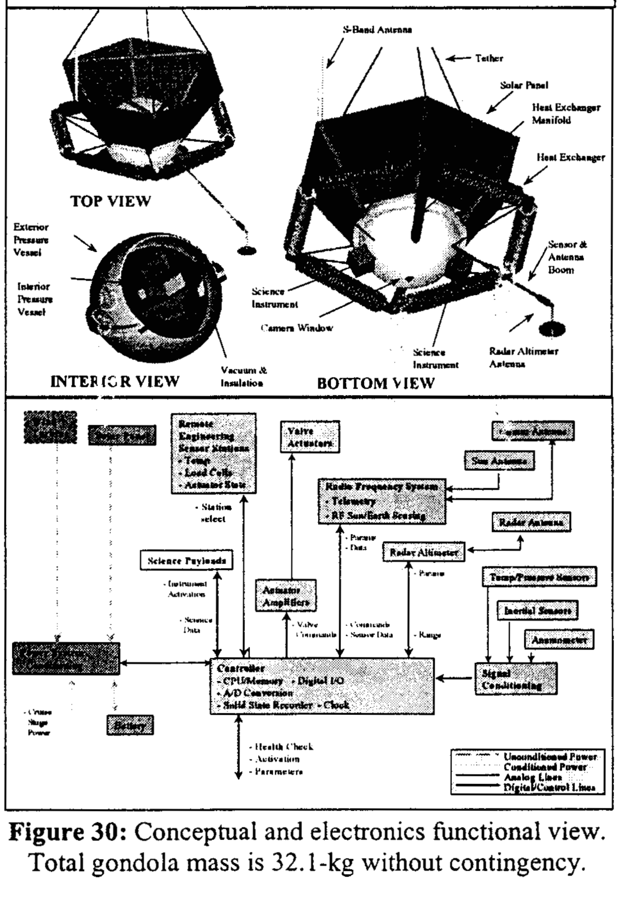


Figure 30: Conceptual and electronics functional view. Total gondola mass is 32.1-kg without contingency.

The gondola is partitioned between components that require a "room temperature/pressure" environment and those that can be exposed to the Venus ambient environment. The gondola design leverages several past JPL activities including: the PIDDP Venus Camera Development (VASSIS), JPL DRDF Venus Gondola Pressure Vessel & Thermal Control Strategies, and Telerobotics Navigation and Control Simulation Research Task. Mass estimates are based on current and near-term projected technology. Trades are performed using both parametric analysis and mission simulations.

Thermal Control

The fundamental thermal requirement is to keep the interior of the pressure vessel at less than 30°C. Conventional insulation (e.g. MLI, gas-filled fiberglass) are insufficient to keep out heat during descents. A vacuum dewar (10^{-4} torr) with insulation reduces heat leak, but temperature still increases unacceptably. Liquid cryogens or expendible solid systems require too large of a support mass. The optimal approach, it appears, is to use a vacuum dewer (with insulation) and "renewable" phase-change material, allowing passive thermal exchange without providing electrical power from the gondola. When the Aerobot re-ascends to the cruise altitude, the PCM is allowed to re-freeze. The baseline PCM selection, lithium nitrate trihydrate, is compared to other options in the chart below.

MATERIAL	PHASE TRANSITION TEMP (°C)	PHASE TRANSITION ALTITUDE (km)	LATENT HEAT (10^3 J/kg)	LATENT HEAT (10^6 J/m³)	DENSITY (gm/cc)
Water Ice (H_2O)	0	58.5	333	306	0.92
Lithium Nitrate Trihydrate ($LiNO_3 \cdot 3H_2O$)	**30**	**56**	**296**	**460**	**1.55**
n-Docosane ($C_{22}H_{46}$)	44	54	249	190	0.763
Sodium Hydroxide Monohydrate ($NaOH \cdot H_2O$) (Highly corrosive)	64	52	272	473	1.72

Figure 31: Thermal control PCM options.

Insulation options include blanket insulation, aerogel, evacuated high density powders, evacuated MLI, and evacuated, rigid floating shields. Blankets are simple, but have too much conductive leak. Aerogel has high radiation leak at high temperatures, and would need to be high density to survive large entry loads. Powders are relatively more massive, but are more tolerant to vacuum degradation. Nevertheless, high outgassing levels may be difficult to handle. An evacuated MLI is lightweight and it should be possible to reduce radiative heat leak (to acceptable levels). The MLI would require careful and tedious detailing around penetrations and seams. A high temperature/pressure "V" shaped seal withstands high pressure, and a copper labyrinth seal along the equatorial flange maintains a hard vacuum. There are concerns about high-temperature compatibility. Shields provide excellent radiative heat transfer protection, but add more mass and complexity (for deceleration load support) compared to the MLI and powder options.

The PCM heat exchanger is a reflux boiler with "diode" operation: it dumps heat above the PCM phase transition altitude and prevents heat leak below the PCM phase transition altitude. External to the exchanger are finned tubes, and internal to the exchanger is an integral finned tube with space for expansion and contraction. The working fluid is ammonia. The outer shell of the pressure vessel has a titanium, white painted exterior and a polished interior. The internal shell is made of thin-shell titanium (or stainless steel). Supports between the two spheres are made of titanium alloy with deceleration load absorbers.

Structure

In addition to environmental constraints, structural requirements for the gondola include maximum compactness to accommodate the aeroshell, minimal gondola penetrations (especially optical windows), and optimal spatial relationships (to promote efficient interconnects). Also required is an unobstructed view for the camera, adequate flow past the PCM exchanger, free-flow past the anemometer, and minimal RF interference with the structure.

The two structural design options are shown in Figure 32. Configuration 1 is a modular structure, allowing simple tie-downs to the aeroshell and convenient antenna attachments. However, the intermediate deck is heavy, shades the solar panels, and s the central load-bearing component. Configuration 2 allows all heavy components to tie directly to the aeroshell (instead of the gondola), provides an unobstructed view for the solar panels, and allows the PCM heat exchanger to have free flow (while descending or ascending). However, The second option provides less modular mounting and positioning.

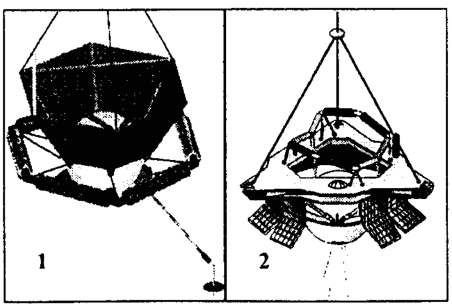


Figure 32: Structural configuration options.

Communications

Due to the volume of data (from imagery), direct-to-earth transmission is infeasible. For this reason, a relay orbiter will store and forward data collected from the balloon. The balloon-orbiter data accumulation rate from the balloon is 100 Mbit per descent and 0.5 Mbit per day at cruising altitude. The command link to the balloon provides only 250 bits/sec. The transmission links are as follows:

DIRECTION OF TRANSMISSION	S-BAND FREQ	FUNCTIONS	DATA RATE (bps)
Balloon-Orbiter	F_{dn}	Data, Doppler	5000
Orbiter-Balloon	F_{up}	Commands, Doppler	> 250
Balloon-DSN	F_{dn}	DVLBI, Doppler	-
DSN-Balloon	F_{up}	Beacon, (Commands)	(>250)
Orbiter/Cruise-DSN	F_{dn}	Data, Doppler	10000
DSN-Orbiter/Cruise	F_{up}	Commands, Doppler	>250

F_{dn} - DSN/Orbiter Receive Frequency
F_{up} - DSN/Orbiter Transmit Frequency

Figure 33: Baseline Transmission links.

S-Band is chosen as the baseline band. It would allow the use of one system on the balloon for both direct-to-earth and relay to orbiter links. The S-Band orbiter needs to actively point during balloon transmissions. and would require dual direct/inverse TX/RX system at the orbiter. Regular communication opportunities are available at each orbit (at apoapsis to maximize beamwidth) during half of the balloon "orbits". One concern is that low bit rates (3 kbits/sec) may require long (> 4 hours) transmission periods (that could create excessive thermal/power loads). The UHF option would provide higher data rates (10 to 100-kbits/sec) at distances greater than 10,000-km. The orbiter UHF antenna would be nadir pointing, with two orbiter systems required. UHF provides communication windows for one-half of the orbits during one-half of the balloon "orbits". These windows are limited to 15 minutes, and the communication zone is limited within the equatorial band. The UHF system also requires another link on the balloon for DSN tracking.

The diagram shows the baseline elliptical (apoapsis: 42,000-km, periapsis: 1000-km), 12-hour, near-equatorial orbit with S-Band communications. Communication at apoapsis provides Venus hemispherical coverage. The orbit is selected to keep apoapsis in the sunlight throughout the 100-day mission. The orbiter relay antenna is sized at 1.5 m, with a quadrant pointing antenna beam of 6°. S-Band transmitter power from the gondola to the orbiter is 10W, which is sufficient for 4-8 hours continuous transmission (without gondola overheating). Communication transmissions occur when the balloon is on the day side, allowing transmitter power to be driven by the solar array. A data return of 172Mbit is expected for an average 6-day balloon "orbit".

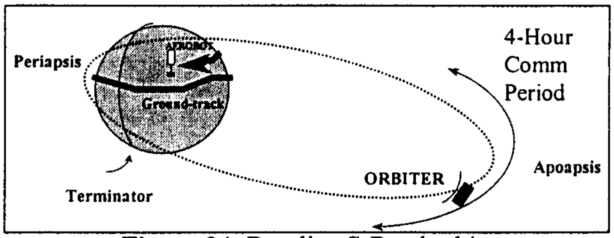


Figure 34: Baseline S-Band orbit.

Avionics

Main controller functions are implemented inside the gondola (pressure vessel) and minimal functions are performed outside. Rad-tolerant, low-power electronics are a must to maximize reliability and minimize mass. Remote stations implement A/D conversion and actuator control.

Several high temperature options are presented for the VEGAS study. Silicon carbide can be used over a wide range of temperatures. However, it has significant yield and reproducibility problems (wormhole structures). Gallium arsenide has shown to work at 450°C, but is usually run up to 350°C to 400°C. Silicon Mosfets / SOI can be used at 350°C, and perhaps higher with process changes. A study has shown that bulk silicon and SOI CMOS process worked at 500°C with increased noise and well behaved degradation. All three options have problems with bonding pad diffusion at high temperatures. Internal electronics use conventional designs, such as the Synova Mongoose-5 rad-hard R3000 CPU or the rad-tolerant PowerPC-603 CPU. Other electronics components include a single board computer, copper data bus, and 1-Gbit solid state recorder.

Included in the avionics engineering sensor suite are inertial sensors, primarily used for tilt sensing. Radio metric sensor options include 1-way doppler, sun direction finding using a parabolic strip antenna, and earth beacon direction finding. The vertical wind-speed indicator is baselined as a propellar anemometer. Ground imaging sensors and radar altimetry is used for ground-track velocity and altitude respectively. Fiber optics can provide data links to the external sensor network. At 500°C, 10-100 samples/sec is a reasonable expectation. A/D transducers may use tuned oscillators whose frequency shifts as a function of voltage. A phase-locked loop is used to pick up the signal after environmental degradation.

Power

The power requirements are 5W for day-time avionics and science functions, 40W for communication every 4-hours out of 12-hours, and 1W for night-time operations (100 hours). The approach on power is to mix both solar and wind power. The solar array is required to survive descents to the surface, but is not required to generate power at low altitudes. The array is sized to allow communication during early morning and late evening operations. Array power during mid-day is far beyond needs. A peak power tracker is used to optimize power extracted from energy as the voltage varies (with illumination). Wind energy is used as a supplement to night-time operations.

Solar cells are only available for half of the Aerobot "orbit". Adequate solar power is only available at high altitudes and low zenith angles. In order to survive high temperatures and sulfuric acid, the cells must be encased in a transparent shell (with welded seals). Present GaAs/Ge cells cannot survive above 450°C, due to contact material diffusing into cells and shorting the junction. Some work has been done on laser induced heating survivability to show 30-minute survivability at 550°C. Two possible technology options include refractory metal contacts and a barrier layer under contacts. The primary solar cell design provides 280-W at 0-deg zenith (at 68-km altitude). A peak power efficiency of 95% is expected. The figure below shows solar array performance.

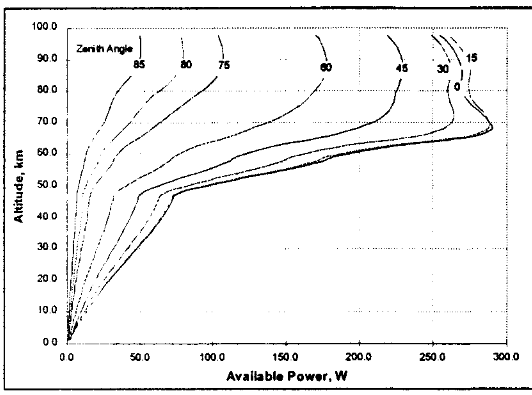


Figure 35: Power solar array performance.

The wind turbine would operate at all altitudes and exploits the Aerobot heat-engine dynamics. Primary design considerations are the use of moving parts at high temperatures and in a corrosive environment.

Counter rotating blades may be needed to prevent gondola rotation. The wind turbine would be coupled with a rechargeable battery to meet nighttime power requirements. The baseline battery is a lithium-ion, at 80-Whr/kg.

Science Objectives and Instruments

The primary science objectives of the VEGAS mission include surface mineralogy and geochemistry, composition and dynamics of the lower atmosphere, interactions of atmosphere with the surface, and out-gassing to the exosphere. The long duration mission provides in-situ measurements at diverse locations. Visible and IR imaging can penetrate the thick atmosphere at a range of resolutions; high spatial and spectral resolution can be obtained. Atmospheric and surface chemistry can be examined at scales ranging from meters to centimeters. Also, the meteorological platform allows sampling of the atmosphere at different altitudes for extended periods of time. The baseline science measurements include surface imaging (IR and visible), wind measurements (updraft), ambient temperature/pressure, atmospheric composition, and both lightning and cloud measurements.

Conclusion

The expected launch date for the VEGAS mission would be from May 5-15, 2007, with arrival at Venus on or about November 1, 2007 (C3<7.5-m/s2, V-inf=3.6-km/s, VOI Delta-V=1320-m/s). The baseline reference launch vehicle and spacecraft is a spinning probe carrier ComSat (310-kg at 30% contingency) and Delta 7925 launch vehicle, respectively. The mass breakdown for the flight system is given in Figure 36.

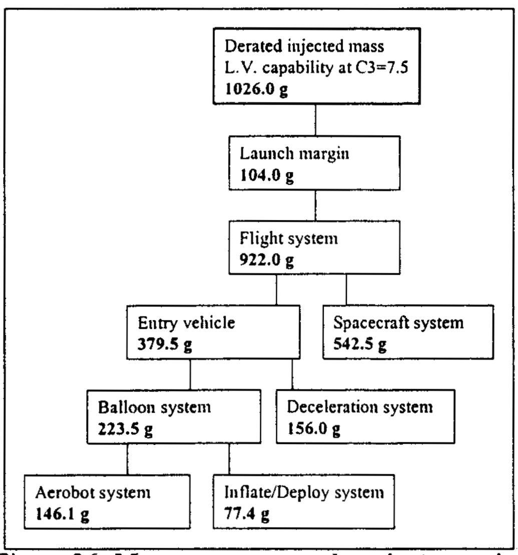


Figure 36: **Mass summary and project margin.**

The foremost technical issues are greatly driven by the harsh Venus environment. Further study is required to model expected surface visibility and wavelength transparancy as a function of altitude (based on cloud occlusion and sunlight scattering). Balloon materials need testing for long-duration, high-temperature exposure (including mechanical properties, permeability, and chemical compatibility). Also, envelope handling procedures are needed for fabrication (seaming), storage, deployment, and flight. Environmental uncertainties also require further refinement, specifically sulfuric acid droplet deposition and wind speeds, wind direction, and air turbulence. ALICE and BARBE type field tests are seen as necessary components to demonstrating PCF balloon thermodynamics for the Venus environment. Further work should center on optimal, compact heat exchanger design and fabrication. The gondola system requires ultra-low thermal conductance to environmentally protect instruments. A combination of deployment load and high-temperature baking tests will validate solar array survivability.

References

Venus Geoscience Aerobot Study (VEGAS) Report, Presentation to Space and Earth Sciences Programming Directorate, JPL, July 28th, 1997.

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