BALLOON EXPERIMENT AT VENUS (BEV)

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Abstract

NASA/Jet Prepulsion Laboratory is designing a return mission to the Venusian atmosphere using a reversible fluid altitude control balloon called Balloon Experiment at Venus (BEV). BEV is a proposed NASA flight experiment to demonstrate key technologies for the operation of advanced balloons in the atmosphere of Venus. This paper includes both the mission profile anti system description of the proposed BEV concept. The selection and thermodynamic modeling of the reversible fluid altitude control technique is not discussed.

Introduction

Planetary exploration is not limited 10 orbiting spacecraft and surface landing devices. The usc of free floating balloons has and will provide excellent scicncc platforms for planetary investigations. in 1985, two balloons were deployed into the atmosphere of Venus on the Soviet-French -U.S. VEGA balloon experiment. These balloons were the first ever placed into the atmosphere of another planet. The VEGA balloons operated for about 2 days at an altitude of 54 kilometers until their batteries were depleted. During this period of time valuable meteorological data were collected by on-board sensors and Earth based radio tracking. A far term goal for advanced balloon technology at Venus is the development of the Venus Flyer Robot (VFR). VFR is a telerobotic balloon which flies and navigates in the Venus atmosphere 10 scientifically interesting landing sites. VFR wiii descend to the hot surface to make simple geochemical and remote sensing measurements and then quickly ascend to the cooler upper atmosphere.

The harsh Venus atmosphere has prevented any intensive exploration of the surface and deep atmosphere. The mostly CO_2 atmosphere at the surface is about 460" C at a pressure of about 92 bars. Conventional electronics systems have problems operating at these extreme conditions. In contrast, at 60 km altitude the temperature is - 10° C and at a pressure of only 0.2 bars. The dense Venus atmosphere is a ideal environment for flying balloons. Onc feature of this thick Venus atmosphere is its opacity in visible wavelengths. This precludes surface imaging in visible wavelengths above a few kilometers altitude. However, altitude control balloons could dip iow into the atmosphere and image the surface at near IR wavelengths (1 pm).

The Jet Propulsion Laboratory has begun planning a balloon technology demonstration called Balloon Experiment at Venus (BEV). BEV development is patterned after JPL's Mars Microrover technology demonstration which is scheduled to fiy on the 1996 Mars Pathfinder mission. Like the microrover, BEV could be carried, piggyback-s[yic, to Venus on another planned mission. This study has shown that BEV is compatible with and could be carried to Venus on an early Discovery mission, with a launch as early as 1999.

The BEV concept is to fly a small, single balloon system which uses ret'ctsible fluid altitude control techniques[1]. The altitude control technique is a simple concept which uses the liquid-vapor reversible phase change of buoyancy fluids to control payload altitude. As the BEV balloon system sinks deeper into tile hot Venusian atmosphere the fluid mixture begins to vaporize inside the balloon, producing a positive buoyancy, and tile balloon begins to rise. This action reverses when the balloon system rises higher into the cooler atmosphere. The mixture condenses, producing a negative buoyancy, and the balloon begins to fail. Stable oscillations, taking on the order of a few hours, can occur at favorable altitude ranges near 50 krn altitude. Several candidate reversible fluid and buoyant gas combinations are available, water and ammonia being the current reference.

BEV will provide a significant advance in the understanding of technologies for the Venus robotic balloons which could lead directly m and enable the design and testing at Venus of a VFR prototype system. The key technologies which will be demonstrated in BEV are 1) the verification and characterization of altitude control concepts 2) lightweight balloon deployment 3) high strength, lightweight balloon envelope design, 4) the testing of balloon navigation concepts, 5) power generation in Venus clouds and 6) a high altitude surface topography mapping experiment.

BEV System Requirements

In order to accommodate a large selection of possible delivery spacecraft, the BEV system has been constrained to be a small, lightweight, Self-con(aincd Venus entry vehicle, with a minimum interference with the delivery spacecraft. Because of these self-conlaincd non-interfering constraints, the BEV system is required (0 be able [0 support communications direct to Earth. An additional mission constraint is that (here be no designed lifetime limitations of the system although leakage of buoyancy gases or battery failure or depletion arc likely potential Ii fetime limiters.

The atmospheric entry dynamics and conditions drive requirements on the system and mission design. The BEV system will be designed to accommodate entry angles up to 70°. This corresponds to maximum axial deceleration loads of 500 g's.

1 n order (o obtain surface topography navigation data in the optical range, the BEV balloon system is required to dip below the Venusian cloud layer during part of each oscillation. The cloud layer extends down (o 47 km altitude. The ammonia-water buoyancy system will provide stable oscillations between approximately 40 and 60 km altitude. The temperature and pressure at these altitudes arc; at 60 km, -10° C and 0.2 bar; at 40 km, + 143° C, and 3.4 bar[2] The solar flux in the cloud layer is estimated to be about 40 W/m^2 [3].

Mission Design

The primary missions goals arc to 1) observe a few balloon altitude oscillations, 2) return in-situ atmospheric data including temperature, pressure, and wind direction, and 3) return optical navigation data of the Venus surface from below the clouds. The primary mission goals must be achievable using only a fully-charged secondary battery available at entry. If adequate solar energy is available and reasonable electrical energy can be produced at tbc temperatures in the clouds, continued operation of the balloon system is expected.

Three sets of data will be obtained and returned to Earth by the BEV balloon system: 1) ambient atmospheric temperature and pressure, 2) balloon system engineering data, and 3) optical navigation topographical data of the Venusian surface. Balloon positioning, on the side of Venus facing the. Earth, will be determined using VLBI radiometric data similar to the VEGA balloons[4]

lkrlh-Venus cruise operations arc limited by carrier spacecraft interfaces and will include only such minimal activities as system check and battery top-off/conditioning. Venus atmosphere operations are limited to data collection and processing. The balloon system will not require and will not be able to receive commands during (he mission. The Earth-based tracking coverage will be determined and negotiated as part of the mission planning process.

Entry and Deployment in the Venusian Atmosphere

After a quiescent cruise period of roughly 4 months, the 25 kg BEV entry system will be placed into the Venusian atmosphere and decelerate in less than a minute from a typical entry speed of 11 km/sec (o subsonic velocities. The entry and deployment sequence is shown in Figure 1. The times, altitudes, and accelerations arc based on the Pioneer-Venus aeroshell design[5], adjusted for the BEV system parameters.

The BEV gondola and balloon arc protected during tbc entry phase by an ablative aeroshell and aft cover. At about 70 kilometers altitude, after the peak accelerations arc over, pyrotechnic devices arc fired and the aft cover is released. The cover acts as a drogue parachute, pulling the balloon envelope away from the gondola anti aeroshell. As the balloon gasses begin to inflate due to the increasing atmospheric temperature, drag will increase and the aeroshell will fall away from the gondola. The aft cover is separated from the balloon envelope by a timed command initiated by an acceleration switch. The balloon system will continue to inflate and reach full positive buoyancy as the balloon descends to 40 kilometers altitude. At this point, the balloon will rise and begin free-flight oscillations.

Engineering data will be collected periodically during the descent through the upper atmosphere. Data collection will be governed by a timer initiated by separat ion from the delivery spacecraft. Atmospheric temperature and pressure measurements will be taken after the aft cover separates from the aeroshell. As the balloon approaches minimum altitude, the BEV Navigation Optical Sensor Experiment (NOSE) will acquire a series of frames of the Venusian surface below the balloon. Most of these frames will be lossy compressed before recording. Onc of the topography frames will be kept at highest resolution for return to Earth.

In order 10 meet the requirement that all of the mission goals be met on a single charge of the secondary battery, BEV will begin sending back the engineering and atmospheric data shortly after the aft cover is jettisoned. The first set of high resolution NOSE data will be sent back to Earth at the peak of the first oscillation. More details of data acquisition and return arc discussed below in the Extended Float section.

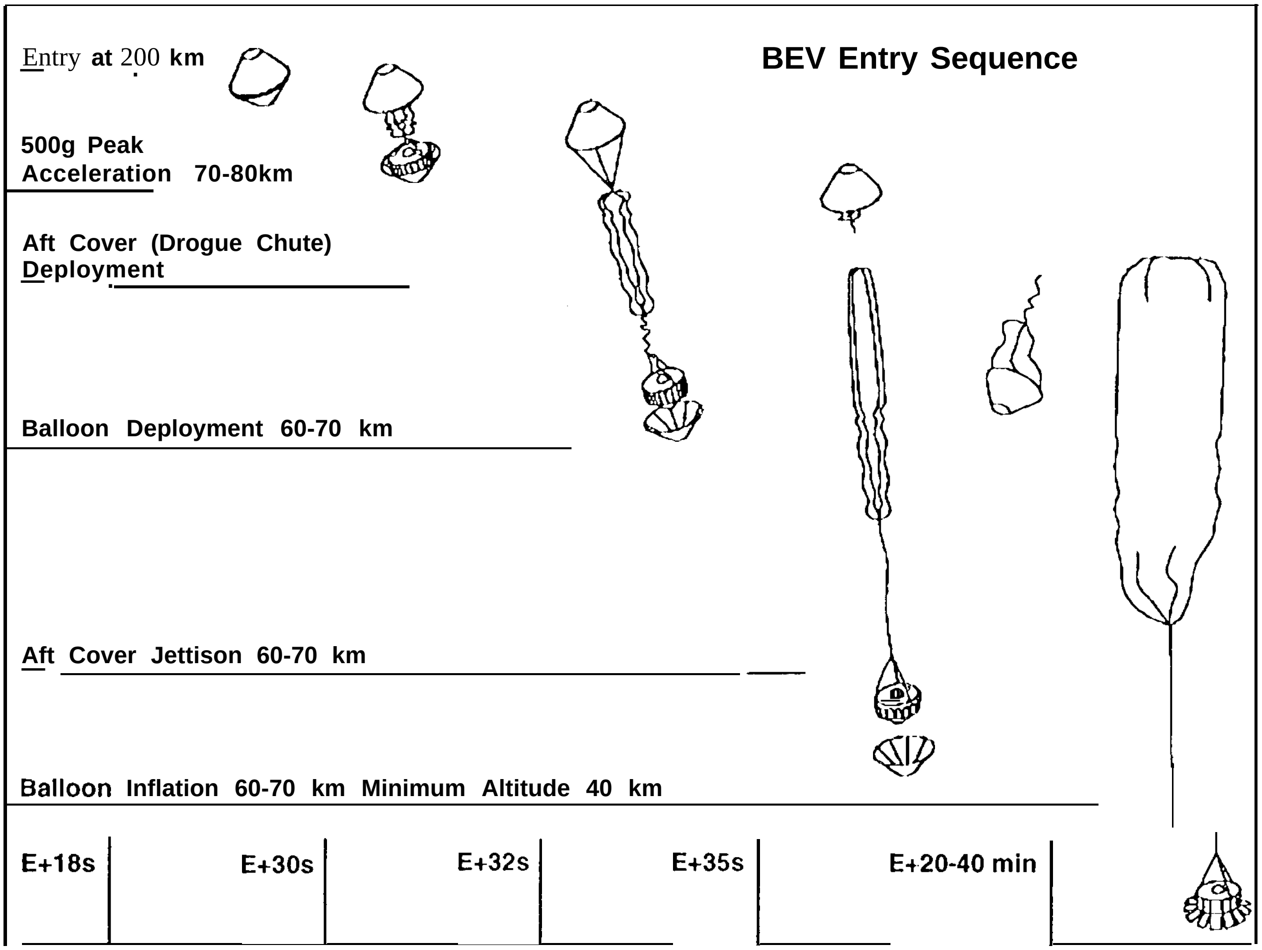


Figure 1. BEV Entry and Deployment Sequence

Extended Balloon Float

Ike-flight circumnavigation of Venus (East to West) in the high altitude winds is expected to take about 8 Earth days. This is defined as one "orbit" of Venus by the balloon system. The BEV balloon system will oscillate between 40 anti 60 kilometers in altitude. A single altitude cycle is estimated to lake approximately 6 hours, with 2/3 of the time spent ascending at a rate of i.4 m/s and 1/3 of the time descending at a rate of 2.8 m/s. This oscillation pattern is illustrated in Figure 2.

A typical extended mission profile consists of continuously collecting atmospheric environment and engineering data at a rate of onc measurement set every 10 minutes **(20** measurements, 8-bit winds) and storing these data **for later playback when** in view of Earth.

Two types of navigation data will be acquired during the mission. At least once per planetary orbit, a high resolution image of the surface will be taken near minimum altitude. These high resolution data are processed and stored for later transmission to Earth. The second type of navigation data is a sequence of overlapping optical navigation frames which will be collected during tile downward low-altitude parts of some cycles. Each frame of optical navigation data will be correlated with the previous frame [o cictct-mine relative surface motion. Each frame will be highly compressed for transmission to Earth. The 1 μm wavelength NOSE data wiii show features on the surface as regions of varying temperature. Since the surface temperature variation is about 10 C from pole to equator, the temprature variations will represent altitude variations[6], thus this data sc(will resemble topography maps. Ground processing of the NOSE data swaths will allow the BEV data sets to be compared to the NASA Magellan spacecraft radar altimetry topography data. A correlation of the two data sets will be used to locate the BEV data on the Magellan Venus map and thereby determine the balloon location and direction of travel. These images will be used to demonstrate optical navigation techniques for a future Venus Flyer Robot.

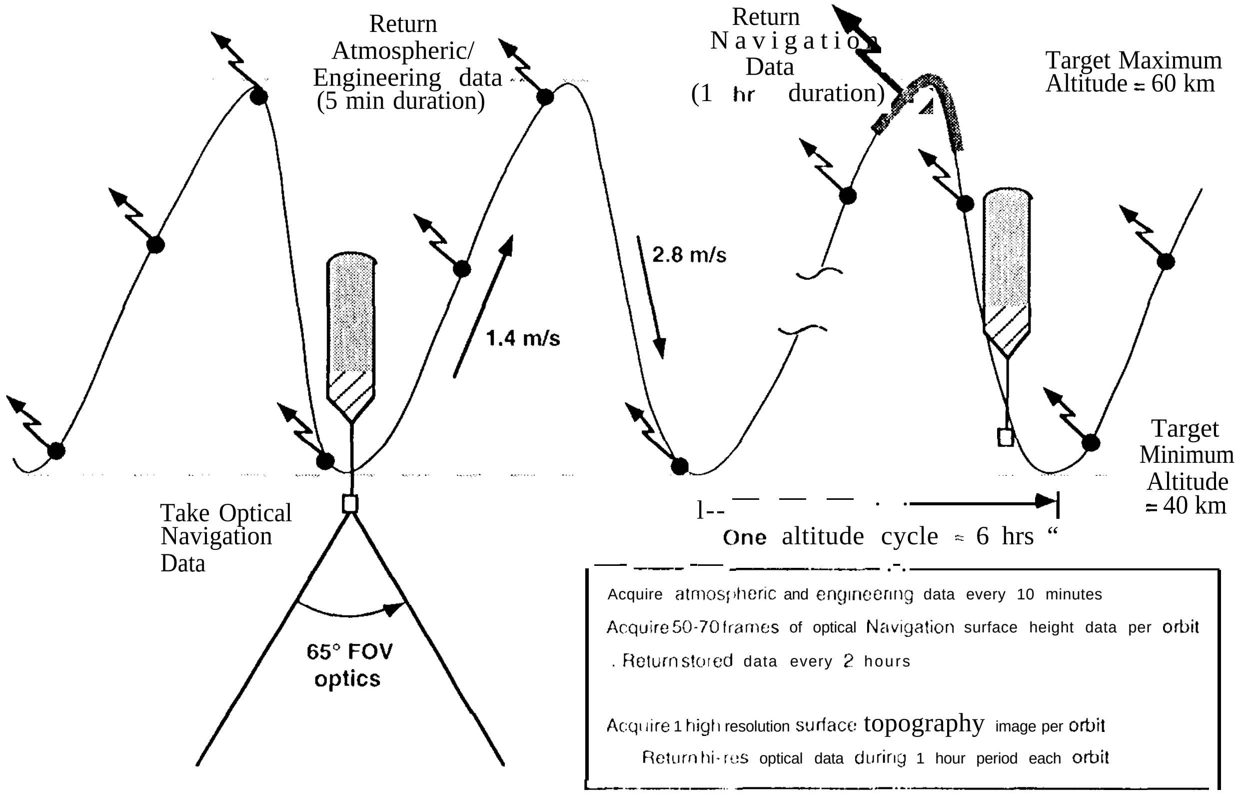


Figure 2. BEV Altitude Cycle Dynamics with Data Acquisition and Return Strategy

Using a low power S-band transmitter and a near-hemispherical coverage antenna, BEV will be able to transmit data direct to Earth receivers for just under half of' each orbit, as shown in Figure 3. The simple onboard sequence for each orbit is referenced to the sunrise and sunset terminators. If lifetime extends more than a few days beyond entry, onboard algorithms will adjust telecommunications data rates and timing in order to account for the varying Earth/Venus geometry. Data rate at mission start is 30 bits/s. BEV will compute the data return period based on observed sunrise and sunset times and stored knowledge of the date and Earth-Venus planetary geometry. The observed time between sunrise and sunset will allow BEV to correct the orbit period, thus removing errors associated with the variable wind velocity.

Data transmissions are of two types. A periodic burst mode consists of 5 minute transmissions every 2 hours when in view of the Earth. This mode includes about 140 seconds of previously stored atmospheric, engineering, and NOSE topography data and about 160 seconds of VLBI tones for position location. A once-per-orbit sustained mode consists of a continuous 1 hour transmission during which the high resolution NOSE data are returned to Earth. The data collection and transmit durations are determined by the available battery power. The 1-hour NOSE data transmission will be able to return an entire frame of data if the planned 10:1 lossless compression ratio is achieved.

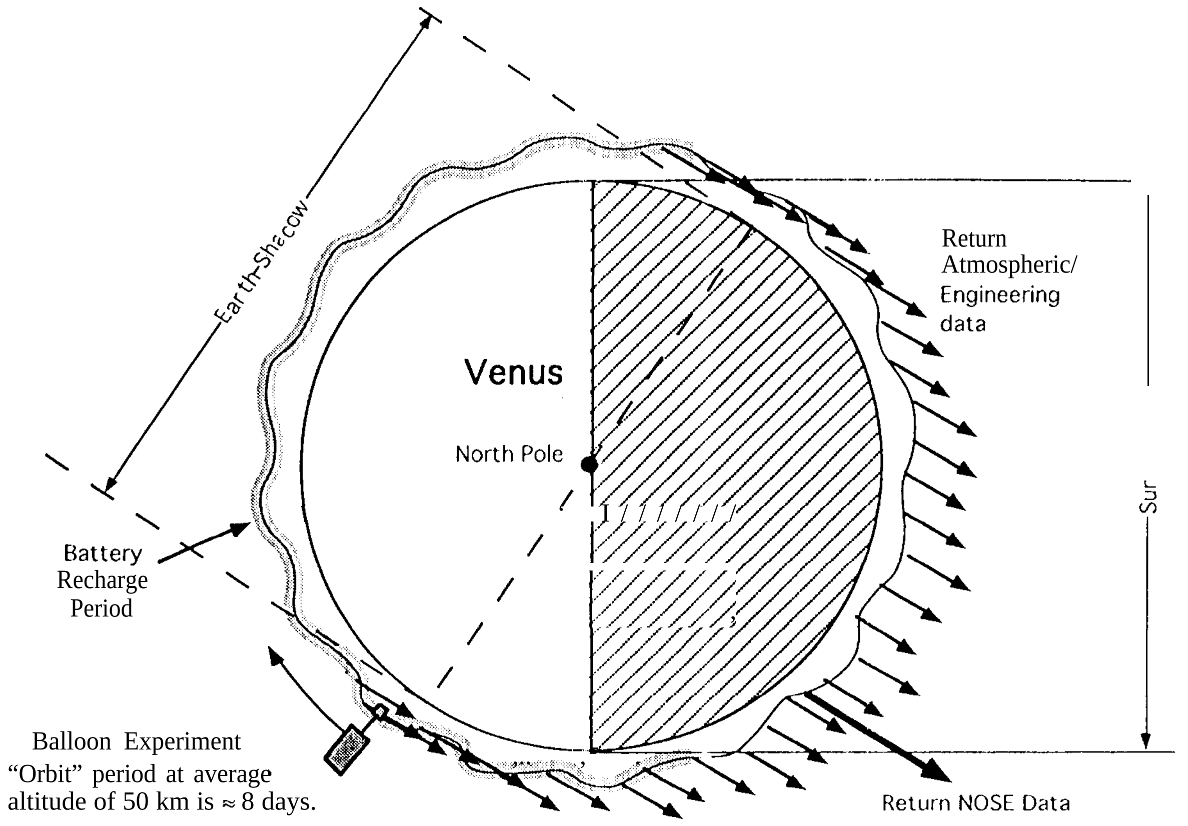


Figure 3. BEV Planetary Rotation and Data Return Cycles

BEV System Design

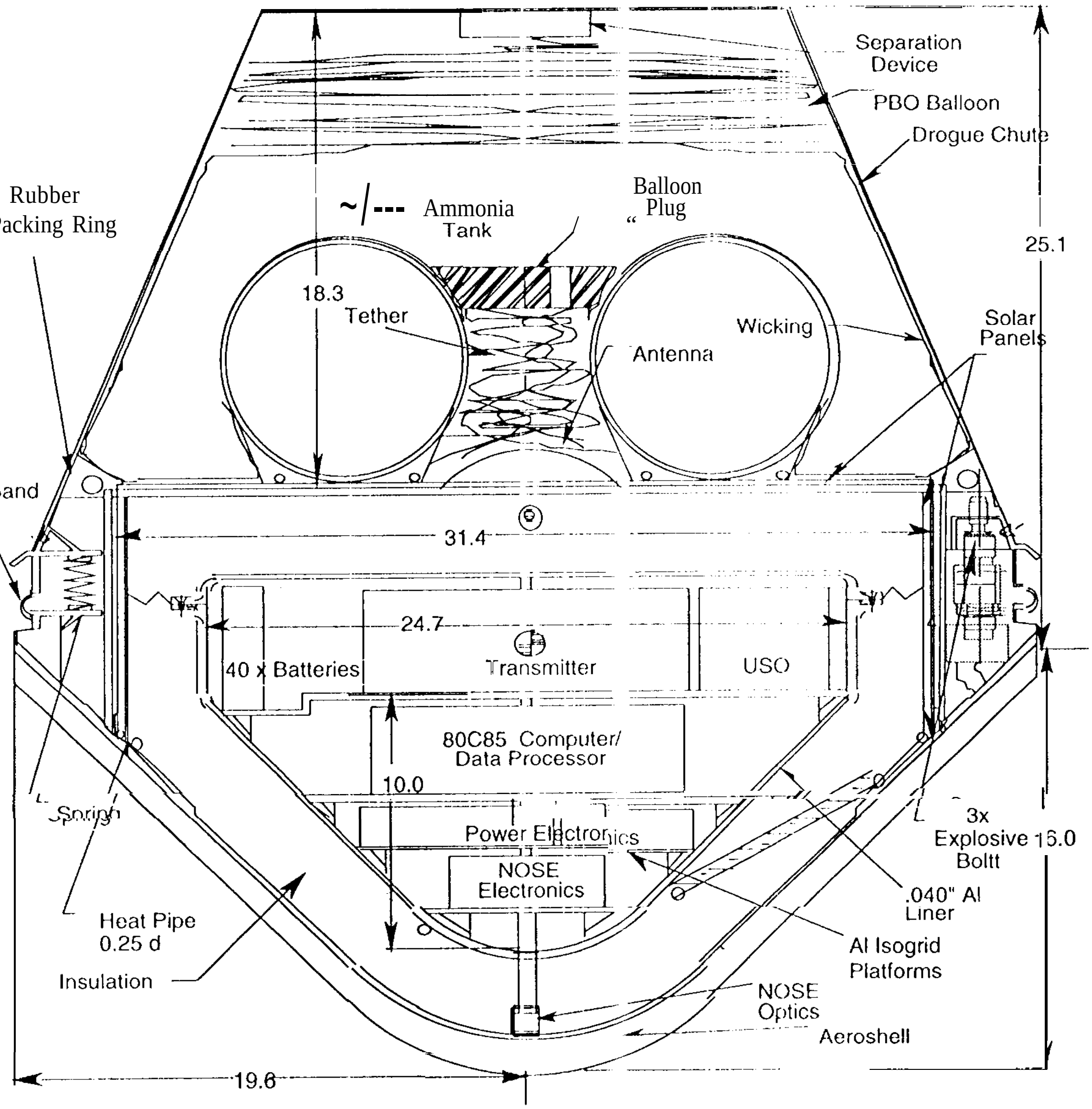
The design of the BEV system was influenced by the many phases of the mission; launch, cruise, entry, deployment, inflation, and normal operation. The BEV cruise and entry system was patterned after the Pioneer Venus Mission[5] design. The top level system requirements for the BEV mission are the following:

Mass <25 Kg
Volume < 24,000 cc (enclosed in a modified Pioneer Venus aeroshell)
Electronic Lifetime at Venus > I week
Temperature Range
 Cruise: -40 to 70 °C
 Atmosphere: -10 to 40 °C
Entry Acceleration Loads
 Predicted: **500 g's**
 Qualification: 700 g's
Data Rate
 30 bits/sec
Reliability
 Single **siring**

BEV Probe Stowed Configuration

The system requirements for this balloon mission are very constraining in both mass and volume. Great effort has been placed on coming up with the bare minimum entry, electronic, and structure configuration. This effort has been combined with the design philosophy of "simpler is better" to produce the cur-rent system design. The BEV stowed configuration is shown in Figure 4.

The scaled Pioneer Venus small probe aeroshell, located at the bottom of the figure, provides entry stability and probe deceleration to subsonic speeds. The 8 kg titanium aeroshell must withstand entry heating and large entry loads (500 g's). However-, the BEV probe only requires its use to the altitude of 60 km. An aluminum based aeroshell would provide sufficient strength and thermal protection for the BEV mission and would have one half the mass of the titanium equivalent. However, it was decided to remain with the titanium aeroshell for its proven entry strength and heritage. If mass becomes an issue as the design matures, an aluminum aeroshell could be implemented.



(All measurements in cm)

Figure 4. BEV stowed configuration

The aft cover contains the balloon system during launch and interplanetary cruise, and assists in balloon envelope deployment. After separation it also provides additional drag and slowing of the balloon system. The top polar section of the balloon envelope is attached to the upper inside of the aft cover. A three section ring, called a V-band, is the mechanism that attaches both the BEV probe to the carrier spacecraft, and the aeroshell to the aft cover.

As discussed earlier, the key to long duration, deep atmosphere operation is altitude control using low boiling point reversible fluids[1]. The two fluids used for the BEV mission are ammonia and water. The water, approximately 2,784 cc, is stored inside the balloon in the stowed configuration. The balloon material is a film made of Polybenzoxazole (PBO). This new material has been chosen because of its ability to withstand the harsh Venus atmosphere all the way to the surface[7]. The ammonia is stored separately in a sealed toroidal tank. The tank has a burst value that activates during Venus atmospheric heating, allowing the ammonia and water to mix inside the balloon.

The balloon film, ammonia tank, and tethering cables arc packed above the gondola into the aft cover. The ammonia tank rests on a rubber ring designed to help distribute the load radially around the solar array panel to protect it on entry. The antenna sits in the center cutout of the toroidal tank.

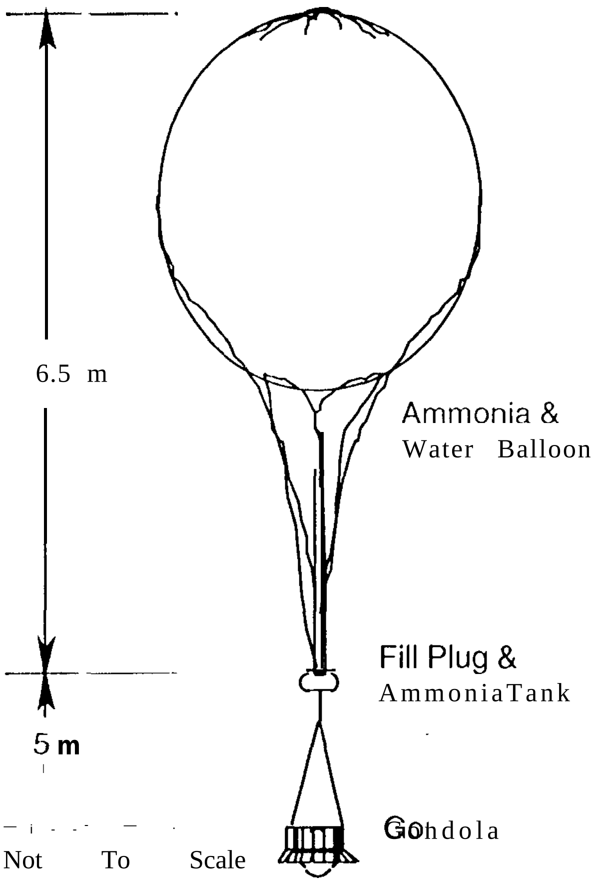


Figure 5. BEV System deployed

Deployment System

The aeroshell, aft cover, and V-band arc held in place by three explosive bolts, with three springs providing a separation force. These bolts and springs arc alternately and equally spaced around the perimeter of the aeroshell. Above the separat (ion devices, a rubber guide ring is used 10 center the gondola within [he aeroshell and to separate the explosives from the balloon film.

During entry, an acceleration measurement system will detect peak entry loads - a short time later the explosive bolt system will be electrically excited. This in turn will allow the spring system to separate the aft cover from the V-Band and aeroshell. The V-band segments into three parts anct falls away. Once separated, the aft cover quickly slows relative to the aeroshell and in the process extends the stowed compact balloon envelope. As discussed earlier the ammonia tank valve ruptures and the balloon begins 10 in flate.

As the balloon descends to the surface, more and more of the ammonia vaporizes, and the balloon system achieves enough lift to begin ascending. The evaporation process takes place as the fluid mixture ($H_2O + NH_3$) settles into the ammonia tank, which acts as an efficient heat exchanger. The balloon in its deployed configuration is shown in Figure 5.

Gondola

The overall shape of the gondola is primarily driven by the shape of the aeroshell and constrained by the volume and surface area requirements. The lower gondola surface structure has a large contact area with the aeroshell. This reduces compressive stress on the structure during entry. The upper gondola surface area must be as large as possible to accommodate solar panels. The wall thickness defines the amount of thermal heating experienced by the electronics. Additionally, the internal volume must be sufficient for sensors and electronics. The structure and insolation design must provide thermal isolated, but also be very thin. This series of conflicting design requirements, combined with the high entry acceleration loads, makes the structure, insolation, and thermal design trades very difficult.

The inner gondola structure houses the electronics and the batteries. A top cutaway drawing of the gondola is shown in Figure 6. To provide minimum packing volume, the batteries arc arranged horizontally. They rest on an aluminum isogrid structure which in turn is fixed to the inner vessel's skin. The isogrid mounting plates arc supported by a central support post,

The thermal system requirements created onc to the most challenging design tasks. The thermal issues are linked back to the need for reversible fluids. An electronic package placed deep into the Venus atmosphere would not last very long duc to the extreme thermal environment. The BEV system solves [his problem by returning to a cooler altitude each cycle. A model of the thermal cycle showing typical temperatures of the gondola's interior and exterior surfaces, is shown in Figure 7.

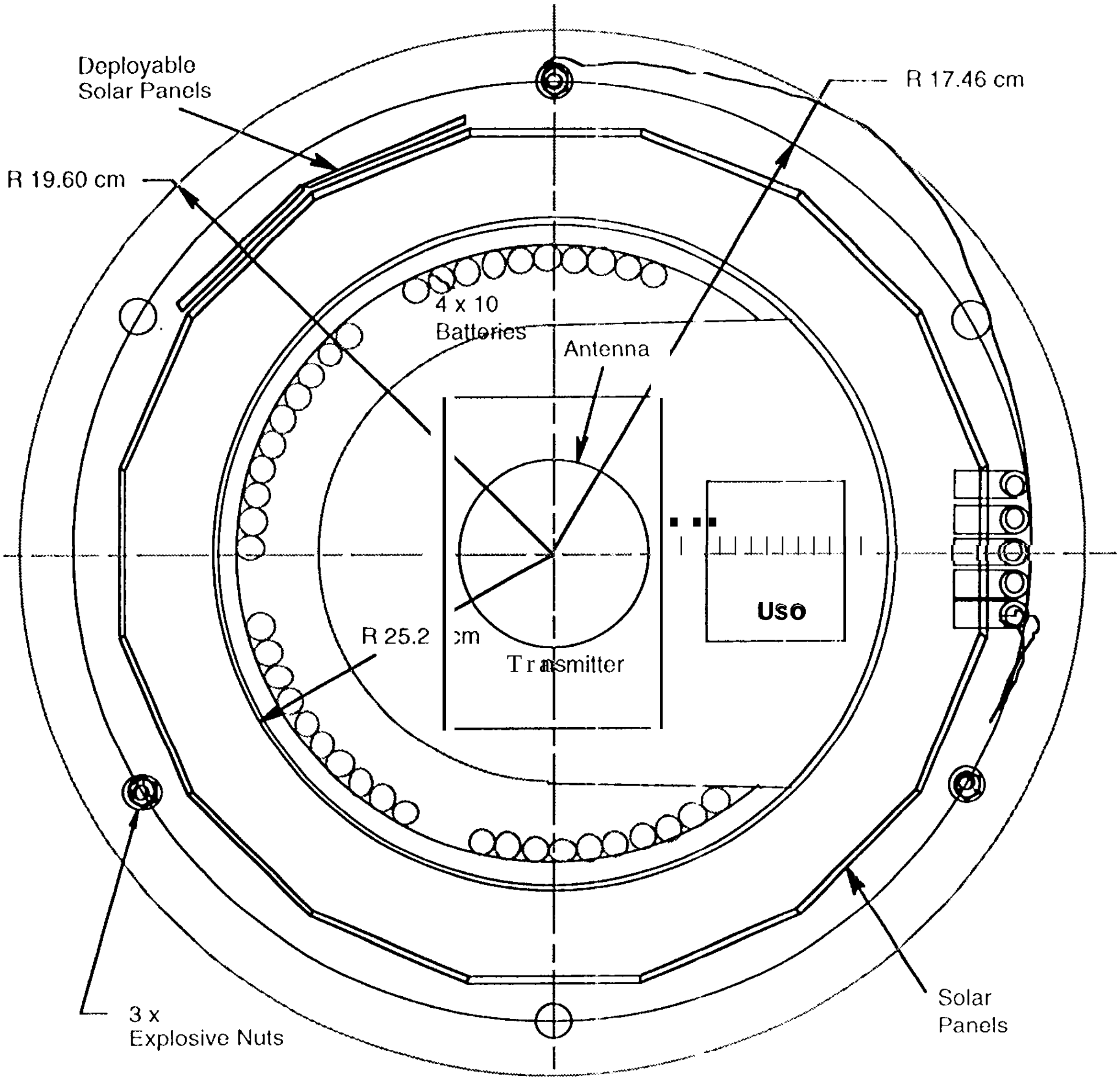


Figure 6 Top cut-away of gondola

The thermal structure contains a reflux heat pipe which allows heat to escape during the upward cycle, but dots not allow heat into the interior during the downward Cycle. This capability can bc observed in Figure 7. Once the heat pipe "[urns on" during the upward cycle the interior IoI1ows the atmospheric temperature.

The combined insulation and structural material selection for the gondola was driven by entry loads and thermal properties. The ability to form a compatible shape with tile aeroshell was also a consideration. The exact material is still being researched, but a silicon or alumina foam insulation arc likely candidates. They have low thermal conductance and relatively high compressive strengths. A sheet of aluminum surrounding the insulation along the vertical edge helps carry compressive loads and provides a flat mounting area for the solar Ceil substrate.

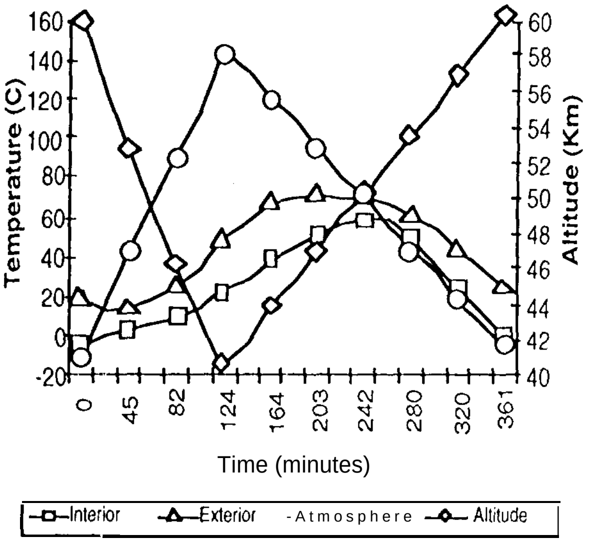


Figure 7 Thermal cycle curves showing the interior (electronics) and exterior (outside skin of insulation) temperatures as a function of altitude. The graph also shows atmospheric temperature vs. altitude.

The construction of the gondola is not an easily dismissed issue. The lower portion of tbc gondola is a complex shape, including the presence of the heat pipe. The internal structure, just inside the insulation, must also be designed to carry the 500g entry loads. This internal skin has been separated into two sections, the lid and body. Because of the small diameter cylindrical shape of the body, a thin 1.14 mm aluminum skin was sufficient. The lid has a small curvature and thus requires a thickness of 2.54 mm of aluminum. The lid is attached to the body using screws through the flanges along the sides. Over this entire structure a 16-sided substrate of solar panels is placed. Everything is constructed in a manner which allows electronic components to be swapped out after assembly if needed.

The BEV system requires a total mass less than 25 kg. The current design mass of the BEV probe breaks down as follows:

Balloon system	2,095 g
Gondola	5,365 g
Reversible fluid	5,010 g
Entry & Deployment	10,531 g
Total :	22,531 g

This leaves a mass margin of approximately 11%. However, this margin could be doubled if the aeroshell was manufactured from aluminum, as stated earlier. The volume margin is only a slightly better, approximately 20%. Both of these margins are narrow for [his phase of the design and require more detailed analysis.

Power Generation

The incoming solar energy is scattered by the Venus clouds to the point of being nearly omni-directional. Therefore, all "surfaces of [fit gondola can be used to mount solar cells. The Venus insolation is approximately 40 W/m^2. This is compared with 1400 W/m^2 at Earth.

The solar panels cover the upper surface and vertical surfaces of the gondola, but not the lower curved surface. This is shown in Figure 8. The lower surface is not used because of the high probability of breaking the flat solar cells during entry. Around the vertical surface of the cylindrical portion of the gondola is a second set of solar panels which deploy by falling away and down from the gondola on simple hinges. The solar cells are high-temperature GaAs with a thickness of only 0.14 mm. The solar panels cover a 0.27 m^2 surface area. The $LiTiS_2$ batteries have a 90 Whr capacity and are re-charged during the 4 Earth day sunlit period of each Venus orbit. The batteries are used for peak power supplement during communication with the Earth and for primary power during the night period of each orbit.

Gondola
(Some Solar Panels
Omitted for Clarity)

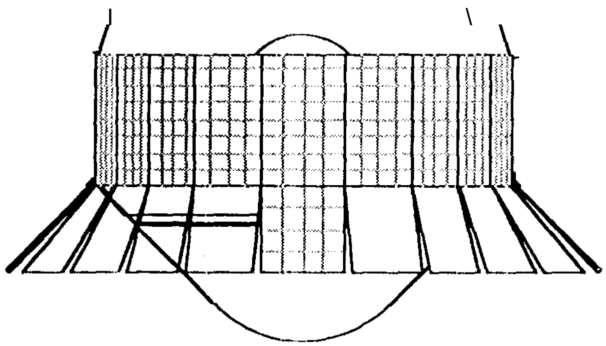


Figure 8. Solar panels cover upper surfaces, with additional deployment skirt folding out after balloon separation].

Data, Communications, & Computer System

The BEV system includes an S-band transmitter with a transmission data rate of 30 bits/second. Because the BEV system will not include a receiver, the system must be autonomous. Once it is assembled for launch, there will be no way of updating or changing any of BEV's on-board programs. Image capture, power distribution, battery charging, environmental data collection, and communications are all performed by the on-board processor.

The BEV computer system is based on the 80C85 microprocessor. This processor has been frown on many different missions and will be flown on the Mars Pathfinder Microrover Mission in 1996. This processor has very modest computational power compared with modern processors, but its 0.33 MIPS provide ample computing horsepower for this mission. The computer has 16K ROM and 32 K RAM on-board. The on-board R OM and RAM will be used for storage and execution 01 the core programs. An additional mass memory consists of i 28K EEPROM and 512K RAM. The EEPROM will be used to store the image and engineering data for transmission. The RAM will be used as a processing and data manipulation environment.

Camera & Engineering Measurements System

The Navigation Optical Sensor Experiment (NOSE) is a near IR (i μm) miniature imaging_ system based on Active Pixel Sensor (APS) technology[8]. The APS allows integration of timing and control electronics, such as analog-to-digital conversion, on a single integrated circuit. The APS camera requires approximately 3 orders of magnitude less power than comparable CCD imaging systems. Without this type of small, iow power system an optical navigation system would not be feasible on this mission.

The NOSE is mounted in the bottom of the gondola, imaging through a 1μm filter peephole cut through the insulation. The NOSE system mass, including optics, is estimated at 200 g.

Conclusion

BEV can make significant contributions to new technical knowledge of Venus balloons. In the category of controlled mobility, BEV provides 1) an understanding of the physics and thermodynamics of reversible fluid buoyancy techniques, 2) a verification of aerodynamic and thermodynamic balloon performance models, 3) a test of the performance and capability of lightweight thermodynamic, solar insolation, optical navigation and atmospheric environment sensors, and 4) some understanding of long-term global navigation of a balloon in the Venus high altitude atmosphere.

BEV's experimental optical altimetry experiment will provide verification of the ability to determine position and velocity from surface topography data. This information is essential for the design of future autonomous navigating Venus balloon missions.

Designing, fabricating, testing and frying the BEV balloon envelope using lightweight, high-temperature-capable materials like Polybenzoxazole provides valuable experience needed to design balloons for operations in the neat- sul'face environment. In addition the BEV balloon envelop wiil demonstrate the design and fabrication of sulfuric acid cloud particle resistant coatings in combination with the high temperature capable materials.

The BEV gondola will be cooled at high altitude (>55 km) by use of diode (reflux) heat pipes which will demonstrate their use and application currently planned for the VFR

Finally, BEV will carry a solar array electrical power generation experiment which will demonstrate solar energy generation at high altitude (40-60 km). in addition, this solar array will demonstrate protection against damage from cloud droplets.

BEV makes a significant contribution to the understanding of Venus balloon technology needed for the. Venus Flyer Robot and is an innovative first step in opening up of the entire planet to robotic exploration of the. surface and atmosphere by balloons.

Acknowledgments

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