Dual Balloon Concept For Lifting Payloads From The Surface Of Venus

Viktor V. Kerzhanovich(1), Jeffery L. Hall(2), Andre H.Yavrouian(3) and James A.Cutts(4) *
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA., 91109

Two highly rated Venus mission concepts proposed in the National Science Foundation Decadal Survey require a balloon to lift payloads from Venusian surface to high altitudes: Venus Surface Sample Return (VESSR) and Venus In-Situ Explorer (VISE). In case of VESSR the payload is a canister with the surface sample plus a Venus ascent vehicle (VAV), which is a rocket that takes the sample into orbit for rendezvous with an Earth return vehicle. VISE is envisioned as a more limited precursor mission where the surface sample is only taken to high altitudes so that non time-critical scientific analyses can be performed. From the balloon point of view, the only difference between these two missions is that the VESSR payload to be lifted is very much larger than VISE because of the inclusion of the VAV.

A key problem is that at the time the Decadal Survey was published no high temperature balloon technology existed to implement either mission. Prior technology development efforts had concentrated on a single balloon that could operate across the entire 0-60 km altitude range, tolerating both the sulfuric acid aerosols and the extreme temperatures of -10 to +460 ºC. However, this problem was unsolved because no combination of sufficiently lightweight balloon material and manufacturing (seaming) technology was ever found to tolerate the high temperatures at the surface. In this paper, the authors describe a solution to the problem based on the idea of using a two-balloon approach. One balloon is optimized for high temperature service in the lower atmosphere, while the second is optimized for high altitude performance. Both balloons can be made from available materials with known fabrication technology. The near-surface balloon will be a metal bellows made of stainless steel or other suitable alloy. The relatively high mass of metal material is allowable in this architecture because only small balloons are needed to lift significant payloads in the dense lower atmosphere of Venus. The second, high-altitude balloon will be made of a more conventional Teflon-coated Kapton film. This much lighter material enables the large balloon volumes needed for expansion in the low density upper atmosphere while the Teflon coating simultaneously provides sulfuric acid protection throughout the ascent.

In operation, the metal bellows balloon will be inflated with either helium or hydrogen gas during the initial descent and landing of the overall vehicle. During the descent and the short stay on the surface, the second, high altitude balloon remains in a thermally insulated container along with the vehicle avionics and other sensitive components. Once the sample has been collected, the payload and the two balloons will be released from the lander and begin to ascend. At a crossover altitude of approximately 12 km, the temperature will be low enough (~370 C) to deploy the high-altitude balloon from its insulated container. The valve that connects the two balloons will then be opened to allow the buoyancy gas from the metal bellows balloon to transfer to the high altitude balloon. The metal bellows balloon will be released once this gas transfer is complete, and the remaining vehicle will ascend to its floating altitude of approximately 60 km while the bellow will float at much lower altitude. Detailed calculations have been performed to design the two balloon vehicle and quantify its performance during all phases of the mission. The paper includes key results from these trade studies for balloon sizing and mass, crossover altitude, and payload temperature.

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(1) Principal Member of Technical Staff, Mobility and Robotic Systems Section, M/S 198-219
(2) Senior Member of Technical Staff, Mobility and Robotic Systems Section, M/S 82-105
(3) Supervisor, Analytical Chemistry Group, M/S 125-109
(4) Chief Technologist, Solar System Space Exploration Directorate, M/S 301-345

Nomenclature

A = fineness ratio (L/D)
B = buoyant force
C_d = drag coefficient
C_{PCM} = specific heat capacity
D = diameter of balloon
d_{ins} = thickness of thermal insulation
d_{pcm} = thickness of the PCM layer
F_l = free lift
g = acceleration of gravity on Venus
HAB = high-altitude balloon
H_{pPCM} = latent heat of PCM
IS = inflation system
L = length of balloon
LAB = low-altitude balloon
M_g = mass of buoyant gas
M_{land} = mass of lander
M_{can} = mass of ascend canister
M_s = mass of flight train
N_t = number of inflation tanks
PCM = phase-change material
S = drag or surface area
T_{melt} = melting temperature
U = wind velocity
V = volume
W = vertical velocity

μ_a = mean molecular mass of atmosphere
μ_g = mean molecular mass of buoyant gas
ρ_a = ambient density
ρ_{ins} = density of thermal insulation
ρ_{PCM} = density of PCM
σ = areal density

Subscripts:
a = atmosphere
b = bellows
can = ascent module
cont = container
IS = inflation system
ins = insulation
k = HAB
m = maximum
s = flight system

I. Introduction

DETAILED understanding of structure and evolution of Venus, though not yet realized, might be the most important goal of the Solar system studies. Being a close sister of Earth in terms of size and mass, and having a thick atmosphere, Venus evolved into waterless deserted autoclave completely covered with clouds consisting of concentrated sulfuric acid. Why, when and how did it happen, what is the composition of the surface and roles of surface and surface-atmosphere interactions, and what are other factors are responsible for this evolution? These are very practical questions that have to be answered to understand and possibly prevent evolution of our Earth in the same direction.

The harsh environment (surface temperature of 460 ºC, pressure of 92 bars) presents a major challenge to any mission intended to study the surface of Venus. So far 8 Soviet Venera and Vega probes have made the first basic studies of Venus surface for 1-3 hours each. This time is insufficient for collection of multiple samples and detailed sample analysis. At the same time it is unlikely that probes with conventional electronics that do not tolerate high temperatures will survive much longer. These considerations drove authors of the National Research Council Decadal Survey [1] (guiding document for NASA Solar System exploration) to name two near-term Venus missions that will allow much more detailed analysis of the surface samples. One of these missions - Venus In-Situ Explorer - would conduct robotic sample analysis in the benign room temperature and pressure environment of the upper troposphere. The other mission of a flagship class – Venus Surface Sample Return – will bring back a sample for precise analysis in laboratories on Earth. Both missions require the lifting of payloads from the surface to upper troposphere (55-60 km), namely a sample canister and analyzing instruments for VISE and rocket with sample canister for VESSR. The only practical vehicle for this cargo lifting is a balloon. Two VEGA balloons operated successfully for two days in benign environment at 53-55 km altitude. They proved feasibility of Venus balloon missions but could not be used as prototype for lifting payloads from the surface.

There have been several mission studies and technology development efforts devoted to the problem of high temperature balloons for Venus [2, 4, 5]. These efforts concentrated on the use of light-weight films that would tolerate the entire range of Venus temperatures and would not be affected by sulfuric acid of clouds. The leading material candidate that emerged was PBO film coated with a noble metal like gold. However, in spite of some progress, PBO balloon technology is still very immature, particularly in the absence of a viable seaming technology, and it is unclear that it can be developed for near- or even long-term missions.

At the same time there are number of available polymer materials that can withstand the somewhat lower temperatures of 350-370 ºC corresponding to Venusian altitudes of 12-15 km. In addition, the near surface atmospheric density is so large (64 kg/m^3) that substantial masses can be floated with very small balloons in this region. These two facts led the authors to the idea of resolving the problem with a two-balloon approach: one small balloon has to tolerate the high surface temperatures while not necessarily be light-weight, while the other much larger balloon has to operate at "moderate" temperatures of 350-370 ºC and be sufficiently lightweight to expand to large volumes in the upper troposphere. Development of this dual-balloon concept follows in the next parts of the paper.

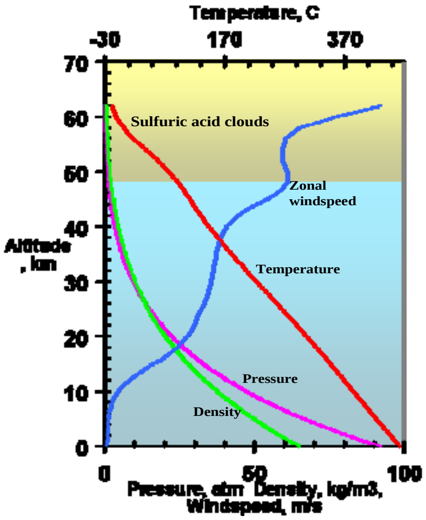

Figure 1. Vertical structure of Venus atmosphere.

II. Venus Environment

We first review the environment where the balloon system has to operate. Figure 1 shows temperature, pressure, density and windspeed profiles [3]. The key values important for balloon design are:

Parameters near the surface (at lowlands) – density = 64 kg/m^3, temperature 463 ºC, windspeed <1.5 m/s, at 15 km – density 28 kg/m^3, temperature 348 ºC, windspeed 16 m/s, at 60 km – density 0.47 kg/m^3, temperature -10 ºC, windspeed 80 m/s. Carbon dioxide is the main constituent (95%); other components are nitrogen (3%), argon (<1%). The atmosphere is very dry though there is ambiguity in the actual water abundance. All atmosphere above 12-15 km is involved in a strong prograde rotation with windspeeds from 10-15 m/s at 15 km to 100 m/s at 65-70 km. The driving mechanism of this super-rotation is still a mystery. In spite of these high windspeeds, turbulence in bulk of the atmosphere is very weak although convection was observed in the 53-55 km where two Soviet Vega balloons flew in 1985. Clouds cover all of Venus all of the time. The cloud deck is near 47.5 km and clouds extend to approximately to 70 km. Clouds consist of concentrated sulfuric acid droplets in a bimodal or trimodal size distribution..

III. Dual-Balloon Mission Concept

The flight system will include two balloons: one of them - low-atmosphere balloon (LAB) – will operate in low atmosphere (altitudes 0-20 km), the other – high-altitude balloon (HAB) will lift payload form 10-20 to 55-65 km.

The entry spacecraft includes a lander with a sampling device and sample transfer mechanisms, sample canister, ascent module, two balloons, inflation system filled with buoyant substance and appropriate structure and thermal protection system (see Figure 2). The ascent module will be customized for each of the two missions. For VISE, it consists of a pressure vessel with instruments for sample analysis, telecommunication system and other avionics, while for VESSR we delete the sample analysis hardware but add the sample canister and Venus Ascent Vehicle (VAV), which is the rocket that will be launched from the upper troposphere to return the sample canister to Earth. All systems will be installed in the aeroshell for safe delivery into the Venusian atmosphere via atmospheric entry. A combination of conventional thermal insulation and phase-change material (PCM) will be used for temperature control and thereby protect the HAB and the inflation tanks.

Though there are could be different ideas for implementation of the LAB we selected the metal bellows as the most technologically mature. The bellows as well as the HAB will be described in more detail in the next section.

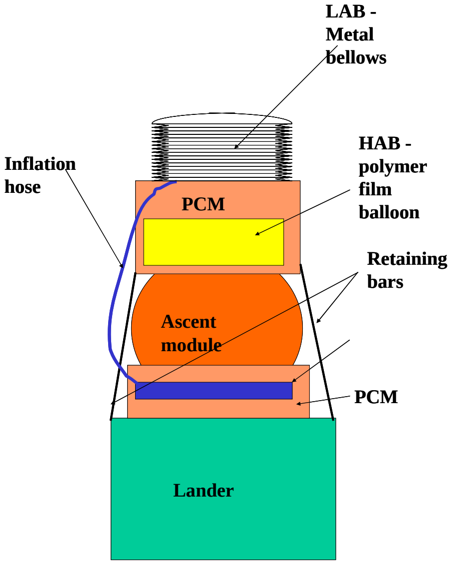

Figure 2. Schematic diagram of the probe.

All phases of the mission from launch to entry in the atmosphere are similar to other Venus probe missions and we will not cover them in any further detail. The lander will be discussed only in parts necessary for operation of the dual-balloon system. There are several possible operational scenarios in the atmosphere that have similarities in major parts but differ in details. We describe one of them below that seems to be the most mass efficient.

Figure 3 shows the atmospheric part of the mission. After entry in the atmosphere the entry vehicle (EV) will deploy a small pilot parachute that will be used as a stabilizer. At an altitude of 53-55 km (where the temperature and pressure are similar to low troposphere of Earth) the pilot chute with the backshell will be separated and second small parachute will be deployed at low subsonic speed and then the front shell will be jettisoned.

When the probe is at an altitude of 3-2 km, the first orifice of the inflation system will be opened and the LAB will begin to inflate. Properties of the thermal control system and sequence of opening of orifices will be designed in such a way to maintain pressure inside LAB equal to ambient pressure. Inflation will be completed near the surface when the pressure inside tanks will equalize with the ambient pressure and the inflation system will be released. Due to that as well as due to LAB buoyancy, the probe descent rate will be significantly reduced. The buoyant force applied to the LAB (located on top of the probe) ensures aerodynamic stability of the probe during descent and makes it possible to release the parachute if the terminal velocity at landing is within safety limits.

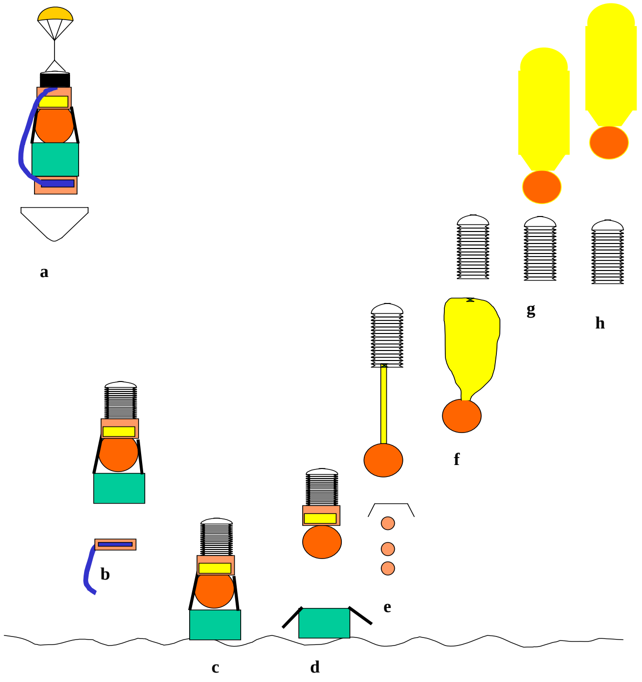

Figure 3. Probe mission profile. *a - aeroshell separation, b - LAB inflation and IS release, c – surface operations, d – launch, e – deployment of HAB, release HAB container, f – inflation of HAB and LAB separation, g – HAB ascent to cruise altitude, h – HAB at cruise altitude.*

Surface operations after landing include imaging, in situ measurements, sample acquisition and transfer of the sample to the ascent module. The storage canister does not necessarily have to be a pressure vessel; the main requirement is to isolate the sample from interaction with the atmosphere during ascent. Duration on the surface is governed by the thermal design of the lander and must be matched to the time necessary for sample acquisition and transfer and subsequent balloon ascent.

After completion of the surface operations the retaining bars (Figure 2) that secure the ascent elements to the lander will be released and the flight train consisting now of the partially inflated bellows (LAB), HAB packed in the container, ascent module and the sample canister (not shown in Figure 3) will begin to ascend. The amount of buoyancy gas would be designed, as for terrestrial balloon launches, to provide a free lift equal to 15-20% of weight of the flight train. Expansion of gas during ascend to higher altitudes will increase length (and hence volume) of the bellows.

At the crossover altitude the bellows will be expanded to its maximum length. At this time the HAB container will be opened and the HAB will be deployed. A combination of shock-absorbing devices (e.g. ripstitches) will be used to limit structural loads on the HAB to within safety limits. The HAB container with the remaining PCM will be then released. This loss of mass will result in increase of the ascent velocity of the remaining flight train. After a short time the valve connecting the bellows with the HAB will be opened and the expanding gas will start to fill the HAB.

In this configuration the flight train continues to ascend. At an altitude where most of the gas has been transferred to the HAB while the remaining gas provides positive buoyancy for the bellows alone, the other valve will close the HAB inflation port. After that the bellows will be released. The bellows and the HAB with ascend module will continue to ascend, initially the bellows moving faster than the HAB. The bellows can be equipped with a simple aerodynamic device providing a side force to move the bellows away from the ascending HAB. Atmospheric windshear will provide additional horizontal separation between these two vehicles. Eventually, the HAB with the ascent module and sample canister will reach the nominal float altitude where the whole HAB volume will be filled with the buoyant gas. The surplus buoyancy gas will be vented at that time and the vehicle will maintain a constant altitude subject to vertical excursions due to turbulence or variable solar heating.

IV. Balloons

A. Low-Altitude Balloon - Metal Bellows

Earlier ideas to use thin metal foils for the LAB are impractical since the foils are too fragile and have no tear resistance. There are not too many ways to build more resilient balloons of thicker metals. A very attractive solution is to use existing hydroforming technology to make metal bellows from thin sheets of stainless steel or titanium. The authors worked with the Gardner Bellows Corp to adapt one of their existing products for balloon testing purposes. This stainless steel prototype (shown in Fig. 4) was 0.35-m diameter with a metal thickness of 7-mil (0.18 mm). The bellows has 70 convolutions and can expand inelastically over 11 times its compressed length when internally pressurized. The compressed length is 0.19 m when its internal pressure is 84 mB less than ambient, while its maximum length is 2.16 m when the pressure inside exceeds ambient by >630 mB. Note that the reusable elastic length is only 0.89 m, expansion beyond this length results in plastic deformation. This prototype was tested in an oven at 460 ºC (right picture in figure 4) then inflated to full length, inspected and checked for helium leaks. No leaks were found.

Figure 4. 0.35-m diameter metal bellows. *a – at $\Delta P=-84$ mB, b – at $\Delta P=114$ mB, c – at $\Delta P=630$ mB after exposure to +460 C*

Bellows size and mass depend on payload mass (mass beneath the bellows), crossover altitude, buoyant gas, bellows material and expansion ratio. Figure 5 shows mass, diameter and maximum volume of hydrogen-filled bellows as function of the payload mass for crossover altitude 15 km. It is assumed that the bellows design is similar to the prototype that we tested: the bellows is made of stainless steel with thickness 7 mil and has expansion ratio 11. As a reference point, the bellows to lift 100 kg payload has mass 42.2 kg, diameter 0.85 m and volume 5.4 m^3. In fact the expansion ratio influence is only on stored volume and not on the bellows mass itself. Figure 5 data shows that the bellows is quite effective: ratio of the bellows mass to payload mass is less than 0.43 for payloads over 100 kg and goes down to 0.2 for 600 kg payload. It is comparable with low-altitude terrestrial balloons and is much better than the ratio for stratospheric balloons. Mass efficiency of the bellows increase also with increase of its diameter.

Bellows size and mass are dependent on the altitude where the payload has to be lifted (crossover altitude) that is illustrated in Figure 6 for bellows with the payload mass 100 kg. The bellows mass increases almost by 70% when the crossover altitudes goes from 10 to 20 km. High-temperature tolerance of the high-altitude balloon is the prime factor in selection of the crossover altitude.

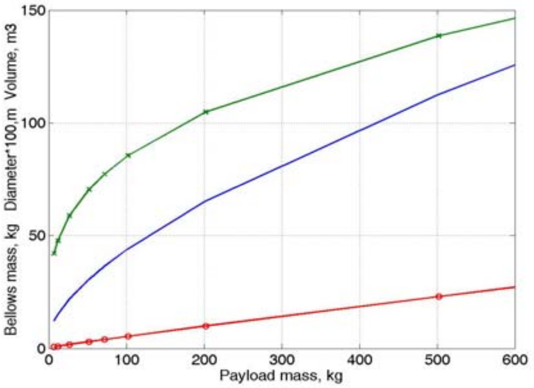

Figure 5. Bellows mass, diameter and volume as function of the payload mass. *Crossover altitude 15 km, buoyant gas – hydrogen. Solid line- mass, crosses – diameter, circles - volume*

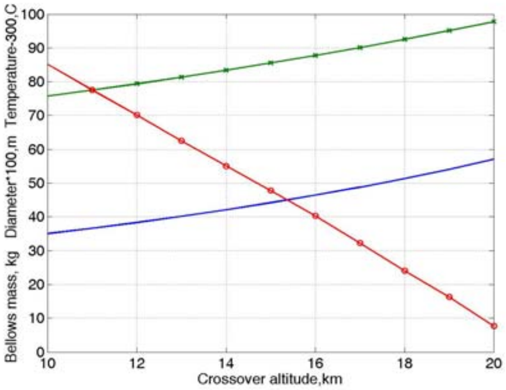

Figure 6. Bellows mass, bellows diameter and temperature of the atmosphere as function of crossover altitude. *Payload mass 100 kg. Blue line - mass, green line with crosses – diameter, red line with circles - temperature*

B. High-Altitude Balloon

Filled volume of the main balloon increases 60 times when the balloon ascends from the crossover altitude of 15 km to cruise altitude around 60 km. The metal bellows will be impractical even if it could be built with such expansion ratio: it would be a 15 m diameter, 900 m height and 70 tons mass bellows to lift 100 kg payload and would require 3500 kg of hydrogen. This very large volumetric expansion requirement means that polymer films or composites based on them are the only practical materials for the high-altitude balloon (HAB) construction. The set of requirements for the HAB is quite challenging: (a) it has to operate from high-temperatures (300-380 ºC) at the crossover altitude to low temperatures (-10…+30 ºC) at the cruise (float) altitude; (b) it has to operate within clouds made of 75-85% concentrated sulfuric acid at temperatures beginning from ~100 ºC at the lower cloud deck; (c) it has to withstand a dense packing inside the entry vehicle and balloon container, (d) it has to survive structural shock loads during deployment at the crossover altitude, (e) it has to have low leak rate. Since float duration from several hours to a day may satisfy as Venus Sample Return as Venus In-Situ Explorer type of missions, the zero-pressure balloon is the design of choice. Even for this design there is no homogeneous film that would satisfy all requirements (a)-(e). Only fluoropolymer films like Teflon can tolerate sulfuric acid and operate in high temperatures, and indeed Teflon is the main candidate for the outer layer . However, Teflon has low tensile strength, especially at high temperatures, and is highly permeable; therefore, it has to be augmented with another high-temperature film that is stronger and less permeable.

Two high-temperature films, polyimide (Kapton) and polybenzooxazol (PBO) films [4] – can be used for the inner layer. PBO film is potentially superior to Kapton, but is still in an experimental phase of development and is currently available only in small pieces. Kapton film is in industrial production for over 20 years and among other applications is widely used for space inflatables. Small weight loss and shrinkage when kept in helium indicate that Kapton retains integrity up to 500 ºC. However, our preliminary tests showed that Kapton becomes brittle in air at 460 ºC, which limits its use as a balloon material at this temperature. At the same time, our test clearly shows no degradation or brittleness at 400 ºC and below. Industrial Kapton FN film is a co-extruded combination of the Kapton and Teflon FEP films that also was tested by the authors at 400 ºC and shown to not degrade or become brittle. The combination of Teflon and Kapton therefore is a good candidate for the HAB provided the cross-over altitude is selected to limit exposure to below 400 ºC.

Since the HAB will be packed and stored in thermally insulated container until deployment at the crossover altitude, the balloon film will not be exposed to high temperatures in the packed state where there is a danger that melted Teflon will adhere to itself. The probability of adhesion is much less after deployment and can be decreased further by a molybdenum sulphide coating

.

The zero-pressure balloon can be built in a cylinder or natural shape. Note that for the ascent phase of the flight, the balloon will be underinflated and therefore have a “bubble-with-tail” shape independent of the nominal balloon design shape. It is only near the float altitude that the balloon will be filled and take the designed shape. In our trade study example we assumed that the HAB is a cylindrical balloon made from Kapton FN film. Balloon volume depends primarily on payload mass and cruising altitude and does not depend on the crossover altitude. Figures 7 and 8 show the HAB diameter and mass as function of the payload mass and cruising altitude. We used balloon with fineness ratio (A=length/diameter) of 4 and made from Kapton 150FN019 film. This film consists of 1-mil layer of the Kapton HN and 0.5-mil layer of Teflon FEP. Areal density of the material is 62.5 g/m^2.

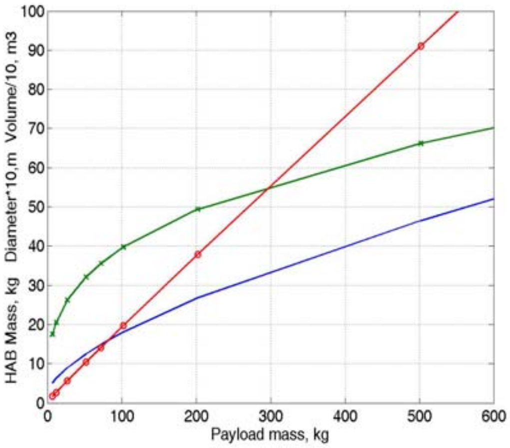

Figure 7. Mass, diameter and volume of the HAB as function of the payload mass. *Cruise altitude 58 km. Mass - blue line, diameter – green line with crosses, volume – red line with circles*

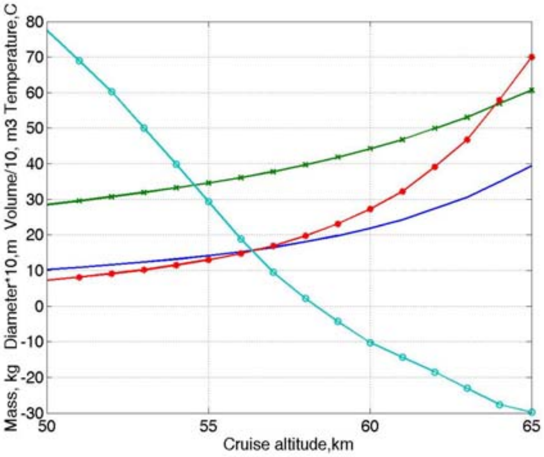

Figure 8. Mass, diameter and volume of the HAB, and temperature of the atmosphere as function of cruise altitude. *Payload mass 100 kg Mass - blue line, diameter – green line with crosses, volume - red line with circles, temperature – light blue line with asterisks*

In general, the HAB is mass efficient and ratio of balloon mass to payload mass decreases from 0.25 to 0.1 for payloads from 50 to 600 kg (cruise altitude 60 km). This efficiency decreases with increase of the cruise altitude. Choice of cruise altitude is dominated by mission objective and available mass. If it is VISE type where the benign environment plays a major role, the optimum cruise altitude would be in vicinity of 56 km where temperature of the atmosphere is close to room temperature while pressure is approximately 0.5 atm. For VESSR mission aerodynamic losses for VAV are dominant and cruise altitude should be as high as possible.

In our example (crossover altitude 15 km, cruise altitude 58 km) the mass of the bellows exceeds mass of the HAB approximately two times in the whole range of payloads. Ratio of the bellows mass to HAB mass decreases when crossover altitude decreases (bellows becomes lighter) or the cruise altitude increases (the HAB becomes heavier). For a given payload the combined mass of LAB and HAB decreases when both crossover and cruise altitudes decrease.

V. Dual-Balloon System Model

We developed a simplified model of the dual-balloon system behavior in all phases from beginning of descent in the atmosphere to ascent to the cruise altitude. The simulated system included all elements as was shown in Figure 2: lander, ascent module, metal bellows (low-altitude balloon), high-altitude balloon packed in the container filled with phase-change material, inflation tanks in their thermal protection system. The COSPAR model of Venus atmosphere for latitudes <30^o [3] was used for environment description.

The LAB is characterized by the diameter D_b, expansion ratio A_b, material density $\rho_{b,}$ thickness e_b and yield strength Y_b maximum reversible length L_{br} and drag coefficient C_{xb}. The cylindrical-shaped HAB is described similarly by diameter D_k, finesse ratio A_k, material areal density σ_k, drag coefficient during ascent C_{dk}, packing coefficient k_{pack} – ratio of volume balloon material to volume of the packed balloon.

The HAB container is modeled as a double-walled cubic box (Figure 9) filled with a layer of vented insulation [5] (thickness d_{ins}, density ρ_{ins}); thermal conductivity of this material was approximated by the thermal conductivity of the ambient atmosphere with a multiplier 1.5. Inside the container another layer of phase-change material (PCM) surrounds the packed HAB. The PCM is characterized by density ρ_{PCM}, latent heat H_{pPCM}, melting temperature T_{melt}, heat capacity of liquid (C_{PCM}) and solid (C_{ice}) phases. Thickness of the PCM layer is d_{pcm}. The container walls have thickness d_{cont} and made of material with density ρ_{cont}. Size of the packed HAB $\mathrm{a}_{\mathrm{kpk}}=\mathrm{V}_{\mathrm{kpk}}^{1/3}$ ($\mathrm{V}_{\mathrm{kpk}}$ – volume of the packed HAB).

The inflation system consists of N_t inflation tanks each containing M_H mass of buoyant gas. Each tank has diameter D_t, length L_t and mass M_t. The tanks are enclosed in the container with insulation material and PCM similar to the HAB container. Corresponding nomenclature is: the vented insulation thickness d_{insis}, density ρ_{iniss};., thickness of the PCM layer is d_{PCMis}. walls thickness d_{contis}. Dimensions of the tanks' pack are length L_{IS}, height H_{IS}, width W_{IS}. Masses of the lander and ascend capsule are M_{land} and M_{can}, maximum diameter of the system during descent is D_{des} and drag coefficient C_{des},

Vertical motion of the system during both descent and ascent simulated with a simple quasistationary model with vertical velocity calculated from the terminal velocity equation

$$W = sign(B_s - M_s g) * \sqrt{\frac{2(M_s g - B_s)}{C_{ds} S_s \rho_a}} \qquad (1)$$

where M_s, B_s, C_{ds}. and S_s are mass, buoyant force, drag coefficient and drag area of the system at any current moment, g – acceleration of gravity (8.87 $\mathrm{m/s^2}$), ρ_a – ambient density. Inflated volumes of LAB and HAB, volume of the pressure vessel V_{seal} as well as external volume of the inflation tanks are used to calculate the system buoyancy. It is assumed that the temperature of buoyant gas inside HAB and LAB is equal to the ambient temperature.

For simplicity linear law approximated the amount of the buoyant gas inserted into the LAB

$$M_{g\,\mathrm{inf}} = R_g (t - t_{0\,\mathrm{inf}}) \qquad (2)$$

where R_g – rate of inflation (kg/s), and t_{0inf} – inflation start time.

We adjusted volume (and mass) of PCM, inflation rate and start time to complete inflation before all PCM in the inflation system enclosure be melted. Inflation begins during descent at low altitudes and is completed before landing. After landing, the system stays with the partially inflated bellows while PCM in the HAB container continues to melt.

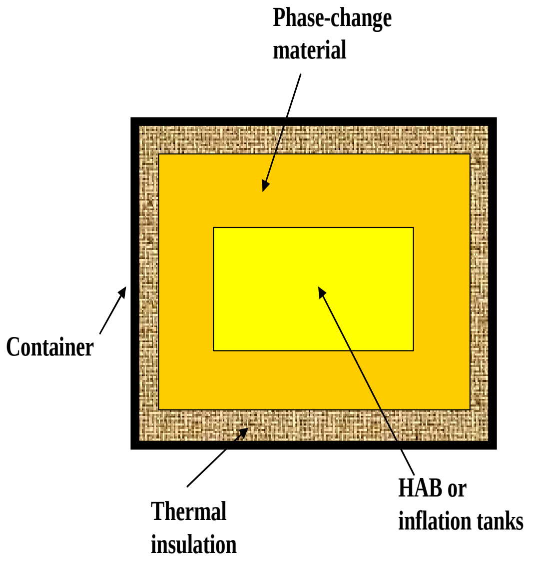

Figure 9. Thermal protection of HAB and inflation tanks

Surface wind is the main risk factor for balloon launch from the surface. A single balloon has to have great volume and length to lift payload from surface to the upper atmosphere. In the presence of wind, the major part of the balloon and the payload will be dragged along the surface during launch and may easily be damaged. Unlike it, the bellows in dual-balloon system will be inflated only to approximately one half its length which by itself is an order of magnitude shorter that length of a single balloon. Also, the aerodynamic drag of the wind (that is <1.5 m/s near Venus surface) is approximately an order of magnitude less than buoyant force and will not tilt it. The system will start to ascend with a flight path angle (angle between velocity and horizontal plane) equal to *arctg (W/U)*, where U is the wind velocity and W is defined by Eq. (1) with system mass and buoyancy

$$M_s = M_{can} + M_b + M_g + M_k + M_{PCM} + M_{ins} + M_{cont} \tag{3}$$

$$Bs \approx \mu_a / \mu_g * M_g + \rho_a V_{can} \tag{4}$$

where μ_a and μ_g – molecular masses of the atmosphere and buoyant gas, M_g – mass of gas in bellows, V_{can} – sealed volume of the ascend payload. Compressibility of the atmospheric gas was neglected.

At the crossover altitude, where the bellows extends for full length and the HAB is deployed, the HAB container with PCM will be dropped. Also the valve between LAB and HAB opens and HAB stars to fill with buoyant gas. The main equations are:

$$M_s = M_{can} + M_b + M_k \tag{5}$$

$$M_{gb} = V_{bm} \rho_a \mu_a / \mu_g \tag{6}$$

$$M_{gk} = M_g - M_{gb} \tag{7}$$

$$F_{lb} = V_{bm} \rho_a - M_b - M_{gb} \tag{8}$$

$$F_{ls} = M_{gk} \mu_a / \mu_g + V_{bm} \rho_a - M_g - M_s \tag{9}$$

$$V_k = M_{gk} \mu_a / \mu_g / \rho_a \tag{10}$$

$$D_k = (6/\pi * V_k)^{1/3} \qquad (6/\pi * V_k)^{1/3} < D_{km} \tag{11}$$

$$D_k = D_{km} \qquad (6/\pi * V_k)^{1/3} \geq D_{km} \tag{12}$$

$$C_d S = \frac{\pi}{4} \max(D_b{}^2 C_{xb}, D_k{}^2 C_{xk}) \tag{13}$$

$$W = \left(\frac{2 F_{ls} g}{\rho_a C_d S}\right)^{1/2} \qquad F_{ls} > 0 \tag{14}$$

The bellows will be released when lift of the HAB will be sufficient to continue ascent on its own while the free lift of the bellows is also still positive. Hence, both vehicles will continue to ascend after separation with their vertical separation controlled by difference in vertical velocities, and horizontal separation by atmospheric wind shear. The ascent rates are given by:

$$W_b = \left\{\frac{2[V_{bm} \rho_a(h_b) - M_b - M_{gbr}] g}{\rho_a(h_b)\, C_{xb}\, (\frac{\pi}{4} D_{bm}{}^2)}\right\}^{1/2} \quad F_{lb} > 0 \tag{15}$$

$$W_k = \left\{\frac{2[V_k \rho_a(h_k) - (M_k + M_{can} + M_{gk} + M_{cont} + M_{ins})] g}{\rho_a(h_k)\, C_{xk}\, (\frac{\pi}{4} D_k{}^2)}\right\}^{1/2} \tag{16}$$

Both the HAB and bellows will ascend to their respective equilibrium cruise altitudes. They will vent buoyant gas upon arrival to maintain near zero superpressure.

For thermal calculations we neglected heat capacity of the inner system (HAB or inflation tanks) and assumed that its temperature is equal to temperature of the PCM. The PCM is initially in a solid phase and maintains a constant temperature T_{melt} during melting. The PCM temperature rises further when all PCM is melted and then starts to boil or transit to supercritical state at the appropriate temperature. The melting rate of PCM is calculated with:

$$\frac{dM_{PCM}}{dt} = \frac{\kappa S_{conti}}{H_{melt} d_{insi}} (T_a - T_{melt}) \tag{17}$$

where S_{conti} and d_{insi} are the surface area and insulation thickness of the appropriate container (HAB or inflation system).

The temperature of PCM in liquid phase T_{PCM} is computed using this differential equation:

$$\frac{dT_{PCM}}{dt} = \frac{\kappa S_{cont}}{d_{ins} M_{PCM} C_{PCM}} (T_a - T_{PCM}) \tag{18}$$

VI. Example of System Simulation

The following example presents simulation results of the dual-balloon system sized to lift an ascent module mass of 70 kg. Such a module is consistent with a VISE type of mission. Mass of the lander is 200 kg. We used bellows and HAB balloons as described in Section IV. Hydrogen is used as buoyant gas, and water as the PCM. Crossover altitude is 15 km (temperature 348 ºC, pressure 33 bar, density 28 kg/m^3.), cruise (float) altitude for the HAB is 58 km (temperature 2 ºC, pressure 0.33 bar, density 0.63 kg/m^3.). The bellows has an expansion ratio of 11, a diameter of 0.91 m, a mass of 43.1 kg, a maximum expansion length of 9.98 m, and a maximum volume of 6.45 m^3. Constructed shape of HAB is cylinder with fineness ratio of 4, a diameter of 3.4 m, a mass of 8.2 kg, and an inflated volume of 123 m^3.

The packed HAB is cube 0.36 m on a side. The layer of water ice PCM around it has a thickness of 0.025 m, and a mass of 22.7 kg. The vented thermal insulation has a thickness of 0.02 m, a density of 150 kg/m^3, a volume of 22.3 liters, and a mass of 3.4 kg. The HAB container made from 1 mm titanium with a mass of 4.3 kg.

The inflation system includes 7 tanks containing 1.2 kg hydrogen each, giving a total hydrogen mass of 8.4 kg (we used of-the-shelve tanks as prototype). The assembly of tanks has dimensions of 1.52 x 0.65 x 0.76 m. The water layer around tanks has a thickness of 0.01 m and a mass of 53.9 kg. The thermal insulation for the inflation system container is similar to that of the HAB with an insulation mass of 17.3 kg, and a container mass of 21.8 kg.

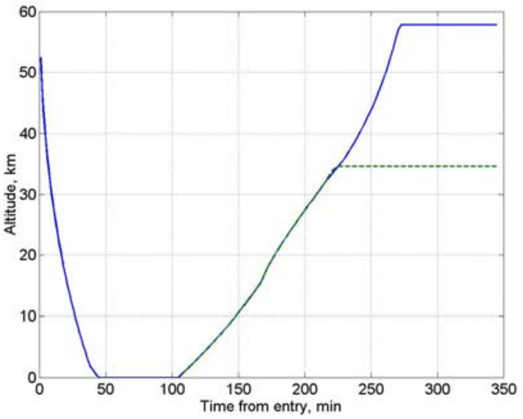

Figure 10. Altitude history. *Solid blue line - altitude during descent and altitude of HAB, dashed green line – altitude of bellows*

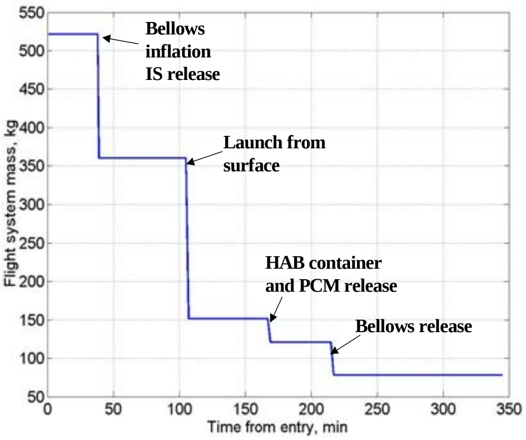

Figure 11. System mass as function of time

The total system mass during descent is 530 kg, with a diameter of 1.5 m and an estimated drag coefficient of 0.7. Durations of operations on the surface is 60 min, after that the ascent system is launched. Mass at launch from the surface is 160.2 kg, free lift in mass units is 22.1 kg.

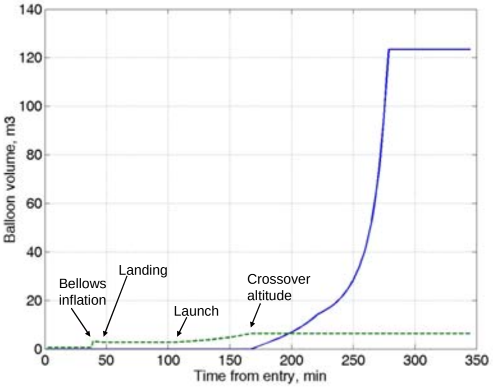

Figure 12. Inflated volume of balloons as function of time. *Solid blue line – volume of HAB, dashed green line – volume of bellows*

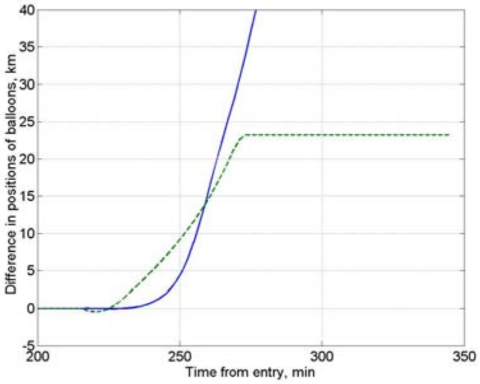

Figure 13. Horizontal and vertical separation between HAB and bellows after bellows' release. *Solid blue line – horizontal separation, dashed green line - vertical separation*

Some results are shown in Fig.10-14. In all charts time scale is minutes from entry in the atmosphere. The probe descends rapidly – in to 38 min to altitude 2km where inflation of the bellows begins. After 5 min of inflation the inflation system is released and descent rate decreases from 10.8 m/s prior to inflation to 5.2 m/s. The probe lands on the surface of Venus in 44 min with vertical velocity 5.1 m/s (which is less than landing velocities of all Venera probes). By this time 11.4 kg of ice in the HAB container in the IS container has been melted. Only 39.8 kg (out of 54 kg) of ice in the IS container has been melted before beginning of inflation The amount of PCM for the IS protection in this provides an ample margin.

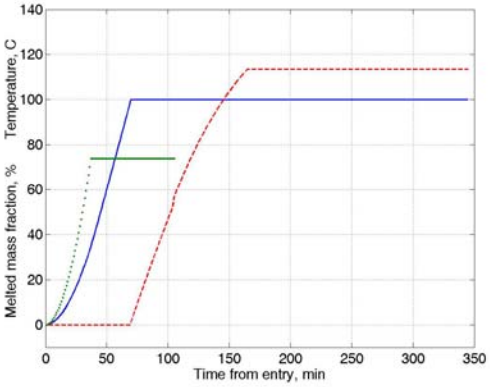

Figure 14. Melted mass fraction and PCM temperature. *Solid blue line – PCM melted mass fraction in HAB container, dotted green line – PCM melted mass fraction in IS container, dashed red line – temperature of PCM and HAB container*

Ascent system mass is 160.2 kg i.e. 370 kg lighter than during descent since the lander remains on the surface and IS was released during descent. By the time of launch from the surface (at *t* = 105 min) the bellows (bellows length at this time is 4.4 m) is inflated and provides free lift 22.1kg (14%) for the ascent flight train.. Ascent rate at launch is 3.4 m/s.

The system ascends to the crossover altitude 15 km in 61 min (166 min after entry). At this altitude the bellows expands to full length (9.98 m), the HAB container opens and the HAB is deployed. By this time all PCM inside the HAB container has been melted and heated further to 113 ºC. The PCM is released when the container opens, the container is dropped off also.

The system has a positive free lift and continues to ascend. Also after the HAB deployment, the valve connecting the bellows with the top fitting of the HAB opens and the HAB begins to be filled with gas venting from the bellows. At an altitude of 31.8 km (*t*=216 min) when most of gas is inside the HAB while gas remaining inside the bellows still provides positive free lift for the bellows itself, the bellows is separated from the HAB. Both vehicles (bellows and HAB with ascent module) continue to rise, bellows moving initially faster than HAB (Figure 13). Horizontal separation between them increases due to windshear. By *t*=227 min the bellows ascends to its cruise altitude of 34 km. The HAB reaches its ceiling of 58 km in 273 min after entry.

In this example our aim was to illustrate system behavior. Further trade studies are required for optimization.

VII. Conclusion

The dual-balloon system described here is the first real approach for high temperature Venus balloon missions like VISE and VESSR. It rests on the use of only existing materials and technology, and its performance can be simulated accurately in the well-known Venus environment. A smaller scale precursor mission will validate the concept. By itself, the metal bellows can be designed to fly in any altitudes from near the surface to 15-20 km while

Kapton film balloons can fly from 15-20 to 60 km. Addition of polyethylene zero-pressure balloons will open all range of altitudes from surface to 75-80 km for balloons, enabling multi-balloon mission proposed in the Venus “White paper”[6].

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