VENUS AERIAL PLATFORM OPTIONS RECONSIDERED

Graham E. Dorrington[1]

[1] *School of Aerospace, Mechanical and Manufacturing Engineering, Royal Melbourne Institute of Technology (RMIT). PO. Box 71, Bundoora, VIC 3083, Australia. Email: graham.dorrington@rmit.edu.au*

ABSTRACT

Some limitations of using super-pressure balloons for probing the middle atmosphere of Venus are discussed. In particular, the accuracy of derived vertical wind velocities obtained from the VEGA flights is questioned. Concerns about using baseline super-pressure balloons to achieve circumnavigation of Venus are raised. Alternatives to super-pressure balloons are reconsidered. To acquire long duration *in situ* measurements of all three cloud layers, further reinvestigation into the use of phase change balloons is recommended. For short duration missions, descent probes offer the highest scientific payload mass fractions and lowest risk.

1. INTRODUCTION

The 1985 flight of the VEGA 1 and VEGA 2 meteorological balloons [1] in the middle atmosphere of Venus was a notable achievement that arguably ranks with major aeronautical historical events. Interestingly, Blamont [2] pointed-out, immediately prior to their flight, that the whole venture was essentially just a "demonstration or feasibility study". Despite the overall mission success, no subsequent (long-endurance) mission to probe the Venus atmosphere *in situ* has yet been approved. Nevertheless, the opportunity remains for near-future Cytherean aerial platforms [3] capable of realising important science objectives [4, 5].

In 2010 Wilson et al. [4] proposed the European Venus Explorer (EVE) as an "M-class" mission to the European Space Agency (ESA) under the "Cosmic Vision Programme", see section 3. Similar to VEGA, EVE specifies a near-spherical Super-Pressure Balloon (SPB) floating at a nominal altitude of 55 km. Although the proposal was commended it was not finally selected by ESA. One criticism was the perception that a SPB floating at 55 km might not be the best platform to obtain samples of the atmosphere at other altitudes, for example, in the lower cloud belt where the controversial "Mode 3" particles exist [6, 7].

The next opportunity for a Venus probe will probably occur around 2020-2025. Consequently, there is now an interval available to re-evaluate exact mission goals and decide the best means to fulfil them. Whilst SPBs are strongly favoured they have some drawbacks and alternative platform options deserve reconsideration.

Some limitations of the VEGA SPBs (and the subsequent data reduction activity) are presented in Section 2. Possible concerns with the EVE 2010 platform proposal (and SPBs in general) are addressed in Section 3. Some alternative platform options are addressed in Section 4.

It is concluded that phase change balloons are promising candidates for long-endurance missions, although, like SPBs, they would have relatively low payload ratios. By 2025, there will probably be an even stronger demand for *in situ* measurements. Hence a short-endurance mission involving a descent probe with a high payload ratio will also become attractive.

2. VEGA BALLOONS

2.1 General Background

The VEGA SPBs were meteorological sondes primarily intended to acquire measurements of horizontal zonal winds through Earth based radio-tracking. They obtained long duration data on atmospheric pressure, temperature, vertical wind, cloud particle backscatter, light intensity variations and possible lightning events [1].

VEGA 1 and 2 were separately deployed at Venus midnight, on 11 and 15 June 1985, at latitudes 7° north and south side of the equator. Within 1 hour they both ascended from the inflation altitude, 50 km, to a nominal float altitude of 53.6 km (corresponding to about 53.5 kPa, 305 K) and drifted westward separated by about 100° of longitude [8]. Both SPBs crossed the terminator (at sunrise) after about 33 hours [1]. The expected 52 hour maximum duration of each payload was limited by battery capacity: a 1 kg unit with an output of 5 W, using 250 $Whkg^{-1}$ lithium cells [9]. Both SPBs actually transmitted for about 46.5 hours descending from an average pressure height of about 53.5 kPa to 58 kPa with several excursions, as low 90 kPa, associated with higher than expected vertical winds (mainly downward) which often exceeded 1 ms^{-1} [10]. The largest downward excursion experienced by VEGA 2 near the end of mission (at 36-37 hours) was associated with persistent downward winds gusting up to about 3 ms^{-1} (although the nominal float altitude was regained prior to final transmission).

2.2 Vertical Wind Velocity Measurement

One of the main scientific objectives of the VEGA SPB missions was to derive estimates of vertical wind velocity. The VEGA SPB design comprised a smooth near-spherical helium-containing envelope about 3.5 m diameter and payload including the vertical flow anemometer hung about 14 m below, see Figure 1. This configuration is far from ideal. In downward relative flows, the anemometer was immersed in the turbulent wake of the envelope. At the nominal float altitude, the Reynolds number is approximately 8×10^5 at 3 ms^{-1}, indicating supercritical flow at this relative velocity and subcritical flow at lower velocities. Vortices would therefore be shed from the envelope with Strouhal numbers in the range 0.1-0.2 [11]. The velocity deficit in the central wake region would also be significant. Furthermore, flow-excited pendulum oscillations of the entire payload unit are possible (with an 8 s period). These factors undoubtedly influenced the anemometer output, but access to raw flight data is needed to investigate the magnitude of any wake effect. Long-period (1-15 minute) anemometer derived vertical velocity fluctuations were measured during the initial fast ascent phase and they persisted when the relative flow fell to 0.5 ms^{-1} [10]. Short period fluctuations (less than 75 s) could not be resolved because of the data collection constraints [9]. Note: relative flows of at least 0.25 ms^{-1} were required to overcome the rotation stiction of the propeller-type anemometer [9].

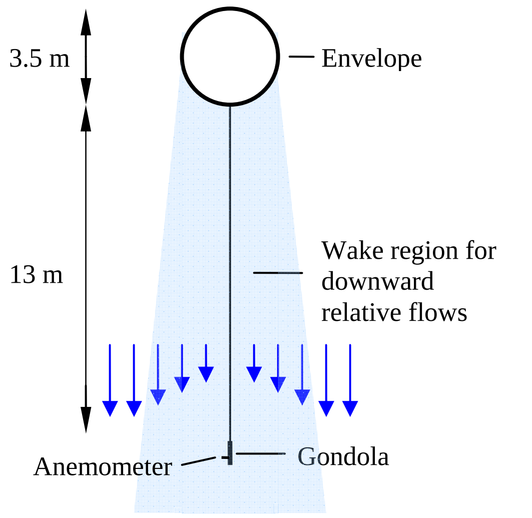

Fig. 1. VEGA Balloon Configuration

During post-flight data reduction, Linkin et al. [10] decided to use the anemometer output to establish zero-relative flow conditions only. Vertical wind had to be derived using barometric data. This procedure involved a number of assumptions and approximations which will be critically considered in the following section.

2.3. Vertical Dynamics

Linkin et al [10] estimated vertical wind velocity by modelling the vertical trajectory. The procedure followed to achieve this estimation is outlined in this section.
Following Nastrom [12], the vertical equation of motion of a (near spherical) SPB is,

$$(M + k\rho V)\frac{\partial^2 z}{\partial t^2} = (1+k)\rho V \frac{\partial w}{\partial t} - F_D - Mg + \rho g V \tag{1}$$

where the drag force is given by,

$$F_D = \tfrac{1}{2}\rho A\, C_D \left(\frac{\partial z}{\partial t} - w\right)\left|\frac{\partial z}{\partial t} - w\right| \tag{2}$$

and the other parameters are as follows:
M balloon system total mass including internal gas;
k apparent (or virtual) mass coefficient;
ρ local ambient atmosphere density;
w vertical wind velocity relative to fixed datum;
z vertical displacement from fixed datum;
C_D steady flow drag coefficient (see Eq. 5)
A cross-sectional area of envelope = πr^2;
V volume of envelope (variable) = $\frac{4}{3}\pi r^3$.

The apparent mass coefficient of a sphere in an accelerated potential (inviscid) flow is exactly 0.5, but for viscous flows with separation it may deviate from 0.5 considerably [13]. Irrespective of this uncertainty, Linkin et al. [10] disregarded the non-steady terms in Eq. 1, since they only strongly influence the short timescale dynamics. They were also forced to use the hydrostatic-derived velocity (based on the local atmospheric pressure P and temperature T) rather than the absolute vertical velocity, i.e. they reduced Eq. 1 to,

$$\tfrac{1}{2}\rho A C_D w_{rel}\left|w_{rel}\right| = \rho g V - Mg \tag{3}$$

where the relative flow velocity is given by

$$w_{rel} = \frac{1}{\rho g}\frac{\partial P}{\partial t} - w = \frac{RT}{gP}\frac{\partial P}{\partial t} - w \tag{4}$$

The vertical winds derived were therefore referenced to isobaric surfaces (pressure height) and not a fixed datum. To estimate the drag coefficient, Linkin et al. [10] used an approximation provided by Scoggins [14],

$$C_D = 0.45 - 0.15\tanh x \tag{5}$$

where $x = (\log_{10}\mathrm{Re} - 5.35)/0.15$ and Re is the relative flow Reynolds number $2\rho r w_{rel}/\mu$, but the accuracy of this approximation remains unclear.
By establishing periods of float equilibrium in the absence of vertical wind, Linkin et al. [10] estimated the average leakage rate in order to deduce a linear decline in the helium mass m_H and total mass M over the mission life of both VEGA 1 and 2. They also derived variations in the spatially averaged internal

helium pressure, P_H, and envelope volume by assuming a linear relation for positive super-pressures,

$$V = V_0(P_H - P)/(eP_0) + V_0 \quad (6)$$

where $e = 0.22$, a non-dimensional envelope elasticity term, was established through unreported laboratory tests [9] with the zero-super-pressure condition, $P_H - P = 0$, specified as occurring when $P_0 = 70$ kPa and $V_0 = 19.4$ m^3. Linkin et al. [10] stated that they could "compute" the internal helium pressure in order to deduce the envelope volume, but in fact it may be calculated directly. Using the ideal gas equation, $P_H = m_H R_H T_H / V$ and $P_{H0} = P_0 = m_{H0} R_H T_{H0} / V_0$, it follows that a simple quadratic equation could have been solved to give,

$$V/V_0 = \{e - p + \sqrt{(e-p)^2 + 4e\theta\sigma}\}/2e \quad (7)$$

where $p = P/P_0$, $\sigma = m_H / m_{H0}$, $\theta = T_H / T_{H0}$.

For small envelope strains, it may be shown that $e = E\lambda/(P_0 R_0 f)$, where E is the modulus of elasticity of the envelope wall, λ is the wall thickness and f is related to the wall material Poisson ratio, $f = 3/2 - 3\upsilon/2$. At the nominal float altitude, $\partial w_{rel}/\partial e \cong 7$, i.e. relatively small changes in the elasticity parameter result in significant changes in the relative velocity derived using Eq. 3 and Eq. 7.

The VEGA envelopes were made from polytetrafluoroethylene (PTFE). In the domain of interest the stress-strain relation for PTFE is non-linear. Furthermore, the E value varies appreciably with temperature. Both these factors place Eq. 6 in doubt.

Linkin et al. [10] also assumed that the average internal helium temperature T_H was equal to the ambient temperature T (after the float altitude was acquired and before sunrise). Small changes in helium temperature will have a large influence on derived relative velocity, $\partial w_{rel}/\partial\theta \cong$ -200. For this reason, Crisp et al. [15] discounted the derived vertical wind velocity data of VEGA 1 and 2 after sunrise. However, during night flight, differences between T_H and T may have been significant. Deviations in T of about ± 1 K from the adiabat were measured [8]. Variations in infrared radiation associated with local cloud backscatter changes, might therefore have contributed to temperature differences of about ± 1 K resulting in derived velocity errors of about ± 0.4 ms^{-1}.

Finally, it should be noted that the possibility of precipitation [5, 16, 17] within the middle cloud belt was not considered by Linkin et al. [10]. Any accumulation of sulphuric acid droplets on the envelope (liquid phase drizzle or possibly falling ice particles) would alter the sensitive weight-buoyancy balance in Eq. 3, and result in significant errors in derived relative velocity and the derived helium leakage rate.

2.4 Vertical Stability of SPBs

The buoyancy of a SPB falls with increasing altitude when it has positive super-pressure, i.e. provides vertical static stability. Ignoring small changes in gravitational acceleration, the buoyancy change with respect to the zero-super-pressure condition is given by

$$B - B_0 = \rho V g - \rho_0 V_0 g \quad (8)$$

In non-dimensional form the buoyancy may written as,

$$b = B/(\rho_0 V_0 g) = pv/\tau \quad (9)$$

where $p = P/P_0$ (again), $v = V/V_0$, $\tau = T/T_0$. From Eq. 7 and 9, it follows that when $\sigma = 1$,

$$b = p\{e - p + \sqrt{(e-p)^2 + 4e\theta}\}/(2e\tau) \quad (10)$$

The partial derivatives of b are,

$$\partial b/\partial\theta = (p/\tau)/(2ve - e + p) \quad (11)$$

$$\partial b/\partial p = (v/\tau)(2ve - e)/(2ve - e + p) \quad (12)$$

$$\partial b/\partial\tau = -pv/\tau^2 \quad (13)$$

For $p \cong 1$, $v \cong 1$ and $\tau \cong 1$ these derivatives reduce to,

$$\partial b/\partial\theta \cong 1/(1+e) \quad (14)$$

$$\partial b/\partial p \cong e/(1+e) \quad (15)$$

$$\partial b/\partial\tau \cong -1 \quad (16)$$

In an atmosphere with a constant lapse rate of L (K/m), $\partial\tau/\partial z = -L/T_0$ and $\partial p/\partial z = -\rho_0 g/P_0$. Hence, when $\theta = \tau$, the approximate change in buoyancy with altitude is given by,

$$db/dz \cong \{-g/(RT_0) + L/T_0\}e/(1+e) \quad (17)$$

Since the term in curly brackets of Eq. 17 is negative, the buoyancy falls with altitude and the rate of decrease (or stabilising tendency) grows as the elasticity parameter increases. However, it is important to note the stabilising effect is quite small; for the VEGA SPBs, $dB/dz \approx$ - 5 N/km.

3. EVE PROPOSAL (2010)

3.1 General Background

The 2010 European Venus Explorer (EVE) proposal specifies a float mission duration of 240 h that would "guarantee at least one circumnavigation of Venus" at approximately 55 km altitude [4]. Science goals include cloud chemistry and measurements of noble gas isotopic ratios, as well as meteorology. Consequently, a much heavier scientific payload than the VEGA SPBs is required (15-20 kg). Also greater power and energy consumption results in the selection of a significantly heavier primary lithium battery (8600Wh capacity, 40 W peak output) supplemented by photovoltaic panels to reduce discharge rates [18].

A smooth spherical SPB of about 5 m diameter is specified to achieve neutral buoyancy with a total flight mass of 60 kg based on an ambient density of 0.92 kg/m^3 at 55 km [19]. This total includes the helium mass (approximately 5.5 kg), but not the helium storage tanks which would be dropped soon after inflation following the proven deployment procedure of the VEGA SPBs (see section 3.5).
Although the EVE proposal was commended by ESA, some areas of possible concern are outlined below.

3.2 Wind Velocity Measurement

According to Wilson et al. [4] the local wind velocity and vector would be measured by the EVE SPB using a gondola side-mounted 3-axis sonic anemometer with ± 0.1 m/s precision. This accuracy level is misleading: in downward relative flows the anemometer would lay in the wake of the envelope (similar to VEGA, see section 2) and in lateral flows the gondola wake would clearly have a strong influence. Placing an anemometer either above the envelope crown, or on a sufficiently long gondola-side-projecting boom mount, would be technically demanding. The simplest way around this difficulty would be to restrict vertical wind measurements to periods when the EVE SPB is immersed in upward relative flows; however, such periods are expected to occur less frequently. Since the EVE SPB was intended to float immediately above a known convective zone (like the VEGA SPBs), according to Crisp et al. [12], it should be expected to drift laterally towards horizontal convergence zones associated with downdrafts (and away from divergence zones associated with updrafts), see Figure 2.

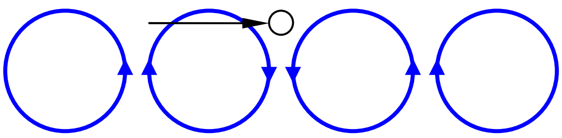

Fig. 2. Lateral drift above convective zone

Prior to VEGA, vertical wind velocities were expected to be less than ± $1ms^{-1}$. Whilst the VEGA measurements may be subject to error (see section 2.2), the existence of vertical winds exceeding ± $1ms^{-1}$ in middle cloud layer is not disputed. Far less severe terrestrial conditions have posed measurement challenges in the past. For example, Wang et al. [20] used balloon sondes to investigate lee side mountain flows but concluded that dropsondes were a more reliable method to obtain vertical wind data.
Assuming that the EVE SPB would experience frequent downdrafts like the VEGA balloons, asymmetric vortex shedding from the smooth spherical envelope would cause lateral lift and pitch oscillations [21]. So measurement of relative horizontal wind would be corrupted. A possible (partial) solution would be to cover the envelope with flow turbulators like a "JIMSPHERE" [14, 22].
If vertical wind velocity has to be derived hydrostatically, as outlined in section 2.2, then it would be beneficial to measure the internal gas temperature and add a load cell between the payload and the envelope to better estimate changes in net buoyancy. The planned upward-looking camera would also yield useful information of the envelope state.

3.3 Atmospheric Sampling Limitations

Wilson et al. [3] write "…a balloon float altitude of 55 km is optimal for the study of the main convective cloud layer", but they continue with: "It may also permit identification of controversial Mode 3 particles (during updrafts) and possibly the UV absorber in downdrafts". While posed optimistically, the modal verbs in this statement imply that atmospheric sampling is potentially limited. Mode 3 particles (with 30 μm radii) do occur at the 55 km altitude [6]. Indeed, if the Stokes drag is assumed, then spherical particles with radii up to100 μm and densities of order 1000 kg m^{-3} could potentially be lifted by upward winds of 3 ms^{-1}. However, in order to sample all Mode 3 particle types strictly *in situ* it could be argued that an ideal platform ought to be capable of a sufficiently slow vertical traverse of the lower cloud layer. Note: excursions below the lower cloud layer could also permit potential surface observations [5, 23, 24].
From an avionics standpoint, established MIL specification limits indicate that prolonged float at about 43 km, where the pressure and temperature are about 250 kPa and 397 K respectively [19], would not present a major technical risk. There are also several candidate materials available to manufacture lightweight envelopes capable of operating at this temperature. Hence a SPB designed to float permanently in the lower cloud deck is certainly feasible, but this lower altitude platform would have significant disadvantages including a longer circumnavigation time and a lower solar input for photovoltaic power generation (resulting in higher system mass).
One possible compromise would be to target a lower initial deployment altitude than specified by EVE (2010), say at 47 km, in order to achieve quick sampling in the lower cloud deck, prior to ascent to the preferred float altitude in or above the middle cloud deck.

3.4 Stability and Endurance of SPBs

SPBs offer vertical stability provided that there is no need to vent helium and provided they do not fall below the zero-super-pressure altitude.

The stability is improved by employing high elasticity envelopes, but the maximal vertical stabilising effect is a quite weak (see section 2.4).
Both the VEGA SPBs achieved their design mission life. However, both experienced strong vertical downdrafts that forced them below the zero-super-pressure condition. The most violent vertical oscillations were experienced by VEGA 2 after sunrise (at 36-42 hours). Young et al. [25] associate these oscillations with gravity waves caused by the Aphrodite mountain range.
There is considerable terrestrial experience with SPB flights within the stratosphere. For example, Herzog et al. [26] describe the terrestrial flights of 27 SPBs in the "Vorcore" campaign. Of all these flights only one mission failed prematurely as a result of excessive vertical oscillations caused by gravity waves, but the failure indicates this risk.
When a SPB is forced below the zero-super-pressure condition by downdrafts, the balloon loses its vertical stability (since its buoyancy no longer varies with altitude). However, this does not present a major problem provided that the buoyancy still exceeds the total system mass. At some stage the downdraft will cease or weaken and the SPB will climb back-up to its original float altitude.
Of greater concern is the heat transfer to the helium gas from the envelope when it is exposed to midday Venus solar conditions. As far as the author knows, no sufficiently accurate modelling has yet been presented to predict the helium temperature response of a Venus SPB in the specified conditions, although two studies are worth noting [27, 28].
Speculation based on *ad hoc* temperature rises is revealing. For example, Eq. (7) predicts that a 10 K step increase at the nominal float conditions of VEGA 2 would be accompanied by a volumetric expansion of about 3%. In still conditions this would result in the initial ascent rate of about 1.3 m/s, causing a further increase in super-pressure and further expansion of the envelope, etc., leading to either the envelope stress limit being exceeded (possibly causing envelope rupture), or helium venting. If the vented quantity is too great and the solar input is subsequently attenuated by cloud (or by sunset) such that the buoyancy falls below the system weight at the zero-super-pressure condition, then premature and irreversible descent would result. If EVE was to suffer from similar midday super-heating, then the *guaranteed* mission goal of one complete circumnavigation of Venus would not be met.

3.5 Gas Vessel Mass and Payload Ratio

One of heaviest components of the SPB system is the gas storage vessel. Phipps et al. [18] assume an optimistic storage vessel mass to helium mass ratio of about 5. When safety margins are considered, a storage vessel mass to helium mass ratio of at least 10 appears to be more likely for a spaceflight qualified system. Hall et al. [29] report successful terrestrial aerial deployment tests of a 5.5 m diameter SPB. In order to fill this envelope with 7 kg of helium, 4 commercial-off-the-shelf carbon composite pressure tanks with a total mass of 75 kg were employed. The vessel for the EVE SPB would probably be of similar mass and size (about 100 litres). This results in the need for a heavier external aeroshell. Hence, although the payload of EVE is about third of its float mass, the actual payload to entry probe mass ratio would be far lower than a comparable descent-only probe. Expressed differently, the demand for long endurance reduces maximum feasible scientific payload mass by a factor of 2 or more.
Note: Phipps et al. [18] consider alternatives to compressed helium. The use of compressed hydrogen only offers modest mass reductions. Carbon-nano-tube storage systems might become available sometime in the future, but current alternative hydrogen storage systems do not offer any significant gains.

4. ALTERNATIVE PLATFORM OPTIONS

There are many possible alternative platform options [3]. Some of the more promising options are briefly presented below.

4.1 Phase Change Balloons

The idea of using saturated or superheated steam (H_2O vapour) to provide buoyancy in the atmosphere of Venus was presented by Dunlop [30] and dates back to earlier studies [31, 32]. More recently, Izutsu et al. [33] and Yamada et al. [34] proposed SPBs filled with H_2O vapour (alone) to float at $z \cong$ 32-35 km.
At $z \cong 42$ km, the pressure and temperature in the Venus atmosphere are P = 280 kPa and T = 404 K respectively. At this altitude, hereafter denoted by $z*$, the saturation line for H_2O crosses the Venus *P-T* profile [32]. Hence, when a Phase Change Balloon (PCB) containing H_2O alone in a freely expandable envelope descends through this "saturation altitude", it will experience a buoyancy change dominated by the volume variation resulting from phase change. When $z < z*$, any liquid H_2O boils causing an increase in buoyancy. When $z > z*$, any H_2O vapour condenses causing a decrease in buoyancy.
Dunlop [30] tacitly assumed that the flight trajectory of such a PCB would converge onto $z = z*$; however, when freely expandable envelopes are employed, phase change actually gives rise to a limit-cycle oscillation of large amplitude about $z = z*$ [31, 32, 35, 36]. Note: if the H_2O is contained in an envelope capable of withstanding super-pressure, then these large amplitude oscillations may be avoided.

Instead of H_2O alone, aqueous solutions of NH_3 have been proposed in the past [e.g., 36]. A solution with about 33% NH_3 by weight freezes at 173 K and would be relatively easy to store during interplanetary flight.
Several other Phase Change Fluids (PCFs) could be employed [3, 32] including ethanol or methanol which both have higher $z*$ altitudes, see Table 1. The main disadvantage of these PCF alternatives is that they all have higher molar mass and result in heavier overall system masses [3].
Mixtures of helium (or hydrogen) and a PCF appear to offer the best overall payload fractions and are therefore the most promising engineering solutions [3].

PCF	Mol.W. / (g/mol)	P^*_{sat} / MPa	T^*_{sat} / K	$z*$/ km
acetic acid	60	0.71	467	33
water	18	0.28	404	42
ethanol	46	0.11	355	49
methanol	32	0.08	332	52
acetone	58	0.07	316	54
pentane	72	0.04	284	57

Table 1. Some Possible Phase Change Fluids (PCFs)

Instead of mixing the PCF in a helium containing envelope, another possibility is to employ separate envelopes to contain the helium gas and the PCF. Such a "Tandem PCB" configuration is depicted in Fig. 2.

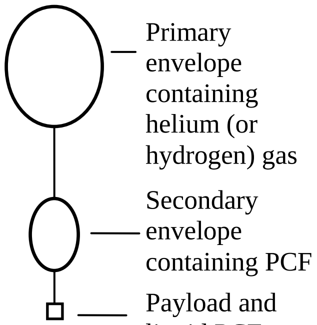

Fig. 2. Schematic of Tandem PCB

Provided that the primary envelope is expandable and the temperature difference between the gas and the surrounding atmosphere remains small, the buoyancy of the primary envelope does not vary widely. The predicted oscillating behaviour is then largely governed by the secondary envelope and the primary envelope mainly acts as a source of near-constant buoyancy, aerodynamic damping (drag) and inertia.
The deployment and float sequence of such a tandem PCB is worth outlining. After probe entry, at a prescribed altitude (say, 70 km), the primary envelope would be inflated with helium (or hydrogen) gas, and the gas storage facility is dropped. At this initial stage all the PCF resides in a liquid container and the buoyancy of the primary envelope is less than the overall PCB weight, hence the system continues to descend. As the system falls below the saturation altitude, $z = z*$, heat is transferred to the liquid container (as well as the secondary balloon envelope) and PCF boiling commences. Consequently, the PCF vapour starts to expand and the buoyancy of the secondary envelope increases. Provided that the increase in buoyancy is sufficient, the downward motion is arrested and then the system rises. As the system ascends up past $z = z*$, heat is transferred from the secondary envelope back to the cooler atmosphere and condensation of the PCF vapour commences. Both the volume and buoyancy of the secondary balloon decrease until the upward motion is arrested and then the system begins to descend again and the whole cycle is repeated, i.e. a self-sustained oscillation is set-up.
A dynamic simulation model was developed [3] in order to verify the oscillatory behaviour of the tandem PCB system depicted in Fig. 2. The model effectively assumes that the PCF remains in a saturated state with the vapour quality varying. This approach differs from Wu and Jones [37], who modelled the actual flight oscillations of a terrestrial tandem PCB using helium and R114 as the PCF [38], but was found to predict similar oscillations.
The predicted oscillation of a tandem PCB using helium and H_2O in still Venus atmospheric conditions is shown in Fig. 3. A limit cycle oscillation with a time period of about 3-4 hours in the range $z \cong 42 \pm 5$ km results. Maximum vertical airspeeds are about ± 2.5 ms^{-1}. The exact oscillation parameters are dependent on the initial system excess heaviness, the overall drag coefficient and the heat transfer rates to the secondary envelope:

i) Increasing the system excess heaviness increases the oscillation amplitude and decreases the period;
ii) Increasing the primary envelope drag coefficient increases the period, but does not alter the amplitude greatly.
iii) Decreasing the heat transfer rate to the secondary envelope increases the amplitude. If insulation is used to reduce the heat transfer rate by an order of magnitude, then it would be possible to achieve an oscillation that reaches $z_{max} \cong$ 55 km (or possibly higher).

In order to achieve a constant amplitude oscillation between z = 35 and 55+ km, a single envelope configuration containing a mixture of both H_2O and helium (or hydrogen) may be a better option [39]. In this mixed-case a diffusion gradient is set-up, which results in reduced heat transfer rates. Experimental work is required to obtain good estimates of the rates involved.

In summary, PCBs offer the potential to automatically traverse the triple cloud layer repeatedly within one circumnavigation, which could be an important atmospheric sampling advantage. The PCB system has the characteristic of being entirely passive and does not require any complex control system. Leakage rates of helium would be lower than the comparable SPB, because envelope super-pressure is not required. It could therefore be argued that PCBs pose lower mission risk than SPBs, even though flight experience with terrestrial PCBs has only been limited to few flight tests to date [38].

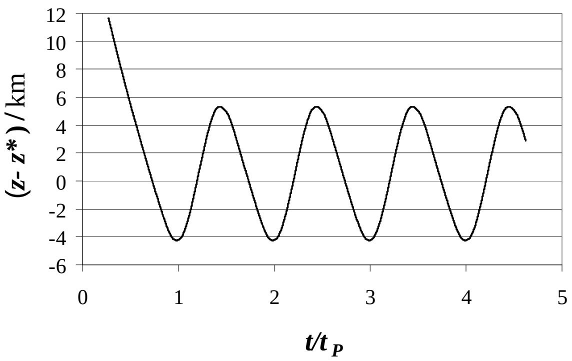

Fig. 3. Simulated Oscillations of Tandem PCB, $z^* \cong 42$ km, $t_p \cong 11900$ s [3]

4.2 Montgolfières

Montgolfière balloons have been proposed for Mars and Titan [e.g., 29], but not often considered for Venus. However, it would feasible to warm Venus atmosphere effectively enclosed in an open-neck envelope to provide buoyancy during night flight by using either:

i) the up-flux of infrared radiation [38] as has been demonstrated by long duration terrestrial flights [39];
ii) free convective heat transfer from a radioisotope thermoelectric power source as per proposals for Titan balloons.
iii) an augmenting magnesium burner, releasing about 16.7 MJ/kg [3].

Compared with all other balloon options the Infra-Red Montgolfière (IRM) appears to offer relatively low overall system mass for given payload. One disadvantage is the need for a relatively large envelope with a lightweight wall, which represents a deployment risk.

4.3 Vetrolet's and Balloon-Kite Systems

As part of the proposed Venera-D and Venera Globe missions, Vorontsov et al. [42] briefly describe the use of a gyroplane and a "Vetrolet", as well as two balloons to float at z = 55 and z = 48 km. The Vetrolet was targeted at z =45-50 km and comprises two parachutes attached to a payload compartment. Such a system relies on vertical wind shear in order to prevent descent.

At 61-66 km altitude the vertical wind shear is 8 ± 2 ms^{-1} per kilometre [43]. Across a 100 m tether a relative dynamic pressure of about 0.2 Pa could be realised. A lifting surface of about 10 m^2, would therefore permit a payload of the order of 1 kg. Hence, the possible active use of para-kites to permit vertical balloon manoeuvres appears to warrant investigation.

4.4 Micro-Balloons

There have been several interesting proposals for using "micro-balloons" for terrestrial meteorology [44] and for Mars exploration [45, 46]. With present technology limits, envelopes with diameters of about 0.6 m would be required to carry payloads of about 200 g in the middle-atmosphere of Venus. Although limited in single-unit capability, multiple micro-platforms could provide distributed atmospheric data.

4.5 Short Duration Missions

Many of scientific goals of the EVE mission [4] and the VEXAG [5] require long endurance. However, in order to perform chemical composition measurements in the middle atmosphere, a descent probe would be sufficient for several key scientific objectives [e.g., 7].

The Pioneer Large (Sounder) Probe [47] was designed for a total atmospheric descent time of about 1 hour powered by silver-zinc batteries (now a relatively heavy battery type). However, it descended from z = 57.9 km to z = 45.4 km in just 13 minutes [48], an average descent rate of 16 m/s. If there was a scientific requirement to extend the duration in this mid-altitude range (using much lighter lithium batteries), then a large reduction in this descent rate could easily be achieved, for example, by using a parafoil-type parachute. Such a descent probe would offer a much higher payload ratio than any balloon system and lower mission risk than any the options discussed above. Note: extending the parafoil idea, constant altitude cruise missions of up to about 50 hours could be achieved on the daylight side using a solar-electric powered flexible parawing-type glider.

5. CONCLUDING REMARKS

While SPBs may have (at present) a relatively high technological readiness level (being closely based on VEGA technology and associated with considerable terrestrial stratospheric flight experience), it does not follow that they will offer the lowest mission risk in 2020-2025. Both VEGA SPBs measured relatively severe vertical winds that on Earth would be more akin to troposphere mountain lee wave conditions, as opposed to the relatively calm conditions of Earth's stratosphere in which large numbers of SPBs have been successfully flown.

Even though both VEGA SPBs achieved their designed mission endurance (a superb achievement), there is no evidence that they were actually capable of circumnavigation of Venus after power-loss. The final violent oscillations of VEGA 2 have been associated with gravity waves caused by the Aphrodite mountain range (avoidable). That does not imply that sufficiently stable flight would have occurred throughout daytime conditions, especially towards midday when strong solar heating might have caused appreciable changes in envelope volume and buoyancy.

If circumnavigation has high priority and traverse of both middle and lower cloud layers is required, then a PCB appears to be a lower risk option than a SPB. Interestingly, the PCB option was preferred in EVE presentations given in 2008-2009 [49]. At that time the SPB option was regarded as a back-up, in case the PCB was viewed (by ESA) as being too high risk [50]. The reason for this position is unclear. Wilson [50] notes that the use of thermal insulation was deemed sufficient to prevent excessive fluctuations in instrument temperature caused by low altitude traverses. Also, the initial deployment-inflation sequence of a PCB poses no greater risk than a SPB, since it occurs at altitudes that may be well matched by terrestrial tests [29]. The only remaining (perceived) risk of using a PCB is the accurate prediction of its vertical oscillations. In this respect, matching tests cannot easily be conducted in the Earth's atmosphere. However the oscillation depends on classical thermodynamics, for which considerable background exists and the vertical structure of the Venus atmosphere is well established. In effect, PCBs provide a dependable buffer that would prevent excessive altitude excursions threatening mission failure. In our solar system, Venus offers the best environment to employ lighter-than-atmosphere vapours for buoyancy modulation. Expressed more succinctly, PCBs are undoubtedly best suited to Venus. The only area of real concern is the relatively low payload ratio that PCBs offer [3].

Further in-depth platform studies are still required. Of all the long duration float options, IRMs may offer the highest payload fraction and consequently also deserve close attention. Eventually, it is hoped that the Venus atmosphere will be repeatedly explored at all altitudes for long durations by a multitude of platforms. However, in the near-term, one high scientific priority must be to get high-fidelity atmospheric sampling payloads into the middle atmosphere of Venus, even if that implies using a short duration descent probe using a conventional parachute system to reduce sink rate.

6. REFERENCES

1. Sagdeev, R. Z., Linkin, V. M., Blamont J. E. and Preston, R. A. The VEGA Venus Balloon Experiment, *SCIENCE*, Vol. 231, 1407-1408, 1986. See also: 8. Sagdeev, R. Z. et al. Overview of VEGA Venus Balloon in Situ Meteorological Measurements, *SCIENCE*, Vol. 231, 1411-1414, 1986.

2. Blamont, J. E. The exploration of the atmosphere of Venus by balloons, *ADV. SPACE RES.* Vol. 5 (9), 99-106, 1985.

3. Dorrington, G. E. Venus Atmospheric Platform Options Revisited. *ADV. SPACE RES.*, Vol. 46, 310-326, 2010.

4. Wilson C. F. et al. The European Venus Explorer (EVE) mission proposal, *EXP. ASTRON*. Vol. 33, 305-335, 2012.

5. Limaye S.S. and Smrekar, S. Venus White Paper for Planetary Sciences Decadal Survey Inner - Planets Panel, Venus Exploration Goals, Objectives, Investigations, and Priorities submitted 2009; http://www.lpi.usra.edu/decadal/vexag/goalsObjsInvFinal.pdf, accessed June 2012.

6. Knollenberg R. G. and Hunten, D.G. Clouds of Venus: Particle Size and Distribution, *SCIENCE* Vol. 203, 792-795, 1979. See also: Knollenberg R. G. and Hunten, D.G. Clouds of Venus: a Preliminary Assessment of Microstructure, *SCIENCE* Vol. 205, 70-74, 1979.

7. Schulze-Makuch, D and Irwin, L.N. Reassessing the possibility of life on Venus: proposal for an astrobiology mission, *ASTROBIOLOGY*, Vol. 2 (2), 197-202, 2002. See also: Schulze-Makuch, D., Grinspoon, D.H., Abbas,O. et al. A sulphur-based survival strategy for putative phototropic life in the venusian atmosphere, *ASTROBIOLOGY*, Vol. 4 (1), 11-17, 2004.

8. Linkin et al. Thermal Structure of the Venus Atmosphere in the Middle Cloud Region, *SCIENCE*, Vol. 231, 1420-1422, 1986.

9. Kremnev et al. VEGA Balloon System and Instrumentation, *SCIENCE*, Vol.231, 1408-1411, 1986.

10. Linkin, V. M. et al. VEGA Balloon Dynamics and Vertical Winds in the Venus Middle Cloud Region, *SCIENCE*, Vol. 231, 1417-1419, 1986.

11. Achenbach, E. Vortex Shedding from Spheres, *J. FLUID MECH*. Vol. 62 (2), 209-221, 1974.

12. Nastrom G. D. The Response of Superpressure Balloons to Gravity Waves, *J. APPLIED METEOROLOGY*, Vol. 19, 1013-1019, 1980.

13. Dorrington, G. E. Drag of Spheroid Cone Airship, *J. AIRCRAFT*, Vol. 43 (2), 363-372, 2006.

14. Scoggins, J.R. Spherical balloon wind sensor behavior, *J. APP. METEOR.*, Vol. 4, 139-145, 1965.

15 Crisp, D. Ingersoll A. P., Hildebrand, C. E. and Preston, R. A. VEGA balloon meteorological

measurements, *ADV. SPACE RESEARCH*. Vol. 10 (5), 109-124, 1990.
16. Cimino J. B. and Elachi, C. Precipitation on Venus: Properties and Possibilities of Detection, *J. ATMOS. SCIENCES*, Vol. 36, 1168-1177, 1979.
17. McGouldrick K., Toon O. B. and Grinspoon, D. H. Sulfuric acid aerosols in the atmospheres of the terrestrial planets, *PLANETARY AND SPACE SCIENCE*, Vol. 59, 934-941, 2011.
18. Phipps, A. et al. Venus Orbiter and Entry probe: an ESA Technology Reference Study, Proc. 8th ESA Workshop on Adv. Space Tech. for Robotics and Automation, ASTRA 2004, ESTEC, Nov. 2-4, 2004.
19. Seiff A. et al. Models of the Structure of the Atmosphere of Venus from the Surface to 100 kilometres altitude, *ADV. SPACE RES.*, Vol. 5 (11), 2-58, 1985.
20. Wang, J et al. Vertical Air Motion from T-REX Radiosonde and Dropsonde Data, *J. ATMOSPHERIC AND OCEANIC TECH.* Vol. 26, 928-941, 2009.
21. Willmarth, W.W. and Enlow, R.L. Aerodynamic lift and moment fluctuations of a sphere, *J. FLUID MECHANICS*, vol. 36 (3), 417-432, 1969.
22. Rider, L.J. and Armendariz M. A Comparison of Simultaneous Wind Profiles Derived from Smooth and Roughened Spheres, *J. APPLIED METEOROLOGY*, Vol. 7. 293- 296, 1968. See also De Mandel R. E. and Krivo, S.J., Radar/Balloon Measurement of the Vertical Air Motions Between the Surface and 15 km, *J. APPLIED METEOR.*, Vol. 10, 313-319, 1971.
23. Moroz, V.I. Estimates of Visibility of the Surface of Venus from Descent Probes and Balloons, *PLANETARY SPACE SCI.* Vol. 50, pp.287-297, 2002.
24. Coustenis, A. et al. Atmospheric Planetary Probes and Balloons in the Solar System. J. Aerospace Engineering Part G, IMechE**.** Vol. 225, 154-180, 2011.
25. Young R. E. et al. Characteristics of Gravity Waves Generated by Surface Topography on Venus: Comparison with the VEGA Balloon Results, *J. ATMOS. SCIENCES*, Vol. 44, 2628-2639, 1987.
26. Hertzog, A. et al. Stratéole/Vorcore – Long Duration, Superpressure Balloons to Study the Antarctic Lower Stratosphere during the 2005 Winter, *J. ATMOS. SCIENCES*, Vol. 24, 2048-2061, 2007.
27. Desjean, M.C., A balloon and its basket in the Venus atmosphere, *2nd Int. Conf. on Numerical Methods in Thermal Problems*, vol. 2, Venice, 1981.
28. Yangpeng L. Thermodynamic Study for Venus Balloon, *ADV. MATERIALS RESEARCH*, Vol. 433-440, 45-50, 2012.
29. Hall, J. L. et al. Technology Development for a Long Duration Mid-Cloud Level Venus Balloon, *ADV. SPACE RES.* Vol. 48, 1238-1247, 2011.
30. Dunlop, R.M., A Steam Balloon for the Exploration of the Atmosphere of the Planet Venus, *J. APPLIED METEOR.*, Vol. 21, 1772-1774, 1982.
31. Linkin, V.M., Moskalenko, G.M., Skuridin, G.A. A possible design for a flight vehicle in the Venus atmosphere, *KOSMICHESKIE ISSLEDOVANIIA* Vol. 20, 128-139, Jan.-Feb. 1982.
32. Blamont, J., Planetary Balloons, *EXP. ASTRON.*, Vol. 22. 1-39, 2008.
33. Izutsu, N. et al., Venus Balloons Using Water Vapor, *ADV. SPACE RES.* Vol. 33, 1831-1835, 2004
34. Yamada, T. Hirose, K. Tanaka., K., et al. Research activities on Venus Atmosphere Balloon Observation mission, *6th Interplanetary Probe Workshop (IPPW-6)*, Atlanta, 2008.
35. Jones, J.A., Reversible fluid balloon altitude control concepts, AIAA-95-1608, *Lighter-Than-Air Systems Tech. Conf.*, Clearwater Beach, FL, May 15-18, 1995.
36. DiCicco, A.G. Nock, K.T. and Powell, G.E., Balloon Experiment at Venus, AIAA-95-1633, *AIAA Lighter-Than-Air Systems Tech. Conf.*, Clearwater Beach, FL, May 15-18, 1995.
37. Wu, J.J., Jones, J.A. Performance model for reversible fluid balloons, AIAA-95-1608, *Lighter-Than-Air Systems Tech. Conf.*, Clearwater Beach, FL, May 15-18, 1995.
38. Nock, K.T., Aaron, K.M., Jones, J.A. Balloon altitude control experiment (ALICE) project, AIAA-95-1632, *Lighter-Than-Air Systems Tech. Conf.*, Clearwater Beach, FL, May 15-18, 1995.
39. Jones, J.A, Innovative balloon buoyancy techniques for atmospheric exploration, *IEEE Aerospace Conf. Proc*. 7, 397 – 402, 18-25 March 2000.
40. Jones, J.A., Heun, M.K. Montgolfiere balloon aerobots for planetary atmospheres, AIAA-97-1445, *12th Lighter-Than-Systems Tech. Conf.* San Francisco, CA, June 3-5, 1997.
41. Malatere, P. Long-Duration Balloon Flights in the Middle Stratosphere, *ADV. SPACE RES.* Vol. 13, 107-114, 1993.
42. Vorontsov, V.A. et al. Prospective Spacecraft for Venus Research: Venera-D Design, *SPACE SYSTEM RESEARCH*, Vol. 45 (7) 710-744., 2011.
43. Sánchez-Lavega, A. Variable Winds on Venus Mapped in Three Dimensions, *GEOPHYSICAL RESEARCH LETTERS*, Vol. 35, L13204, 208.
44. Manobianco, J. How Nanotechnology Can Revolutionize Meterological Observing with Lagrangrian Drifters, *BULLETIN AM. METEOR. SOC.* Vol. 89 (8), 1105-1109, 2008.
45. Bickford, J. et al. Large Scale Deployment and Operation of Distributed Sensor Assets Optimized for Robust Mars Exploration, *Proc. NASA/DoD Conf. on Evolved Hardware*, 173-182, NASA Ames, June 29 – July 1, 2005.
46. Zubrin, R. et al. Mars Micro Balloon Probe http://www.eoss.org/eoss043/EOSS43summary.pdf accessed, June 2012.

47. Bienstock B.J. Pioneer Venus and Galileo Entry Probe Heritage, *International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, Lisbon, Portugal, 6-9 October, 2003.
48. Seiff, A. et al. Structure of the Atmosphere of Venus up to 110 Kilometers" Preliminary Results from Four Pioneer Venus Entry Probes, *SCIENCE* Vol. 203, 787-790.
49. Chassifiere E. et al. European Venus Explorer: an in situ Mission to Venus using a Balloon Platform. *37th COSPAR Scientific Assembly*, Montreal, Canada, July 13-20, 2008. See also: Chassifiere E. The European Venus Explorer: a Mission for Better Understanding the Climate Evolution of Terrestrial Planets. Int. Conf. Comparative Planetology, Noordwijk, The Netherlands, 11-15 May 2009.
50. Wilson. C. F., Report of Oxford Venus Entry Probe (VEP) meeting 25 January 2007, http://www.atm.ox.ac.uk/user/wilson/VEPoxford/Oxford_VEP_meeting_Jan07_report.pdf accessed June 3, 2012.