THE EXPLORATION OF VENUS :

BALLOONS FOR THE VEP MISSION

by Jacques Blamont (CNES)

After the major advances on Venus science obtained with the Soviet Venera soundes and the Nasa Pioneer Venus and Magellan missions, it is clear that the major problems concerning the Venusian atmosphere continue to be :

1) the nature, causes and features of the general circulation,
2) the chemistry and physics of sulphur and chorine components, from the ground altitude to the top of the clouds.

To these major objectives for the exploration of Venus can be added a long term effort :

3) the preparation of sample returns.

It is not possible to reach any serious result in any of these three directions without long-lived in situ measurements. Only aerostats provide the possibility of the prolonged monitoring which is required in atmospheric studies.

Therefore it is proposed to devote the VEP mission to the deployment of a flotilla of balloons at different altitudes.

The mission would consist of :

1) A polar orbiter devoted essentially to two major functions :
    - relay for balloon data,
    - radar tracking and positioning of balloons.

   Complementary scientific instruments can be added if mass and budget are available.

2) Aerostats :
    - 24 devoted to the description of the general circulation at four different levels,
    - 3 devoted to the chemistry at different levels.

3) Drop sondes launched from the balloons

Fig. 1 presents the technical challenges of such a mission in three major domains : balloon realization, power supply and electronics. The problem of instrumentation is not treated.

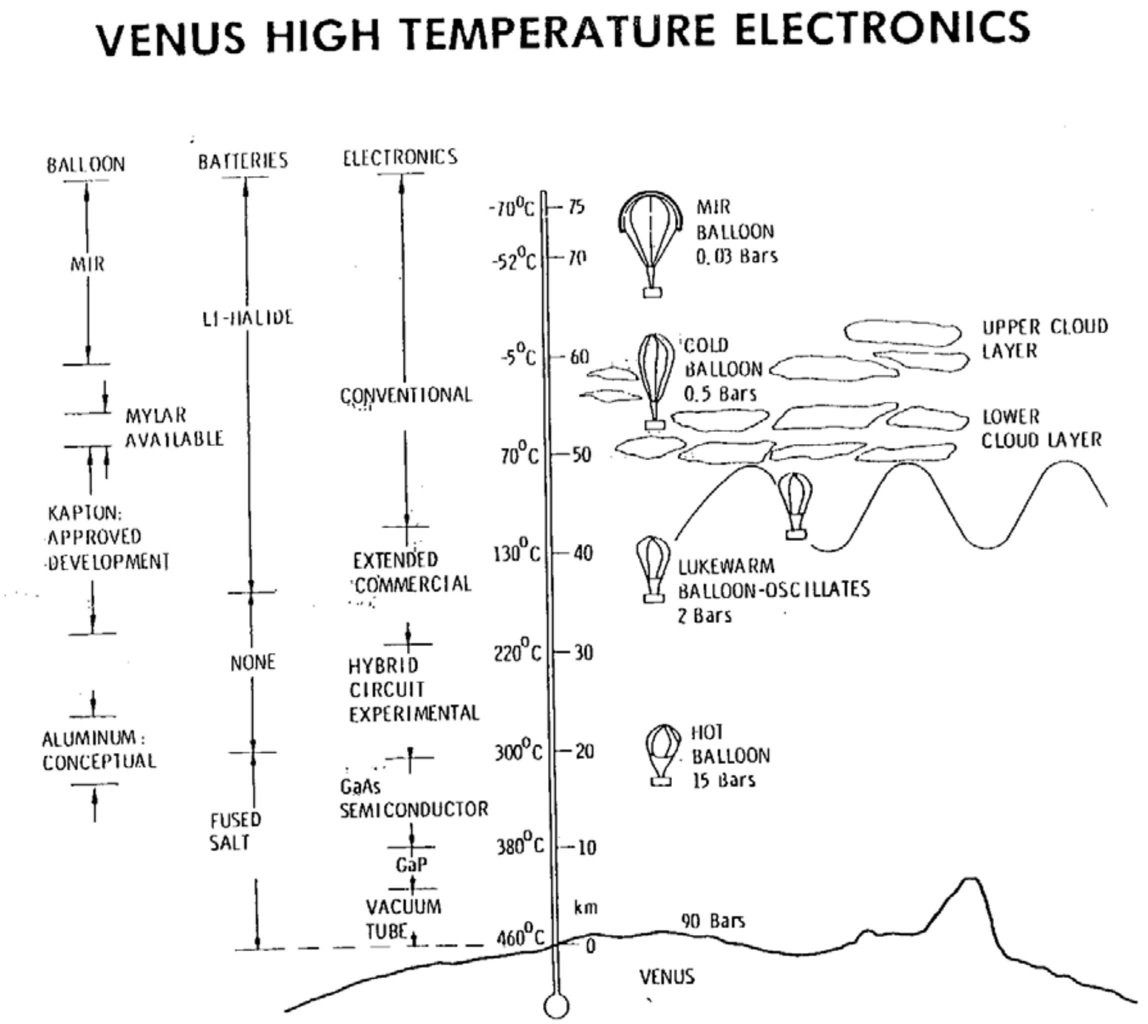

Figure 1

1 – CONCEPTS FOR VENUS BALLOONS

A major feature of the Venus balloons should be their capability of reversible vertical excursions, which can be achieved by two different methods.

1) Reversible phase changes in the carrier gas

The principle relies in placing inside a closed vessel a compound susceptible to exist in gaseous phase, providing buoyancy, above a transition temperature (in the Venus atmosphere, below a certain altitude), and to condensate to a liquid phase below this temperature (in the Venus atmosphere, above the altitude where the transition temperature is reached). The concept, presented around 1977 by J. Taillet and J. Blamont to the CNES-IKI Venus balloon program which became Vega later, has been elaborated in numerous internal CNES/ONERA reports by M. Romero, J. Bezaudun and M. Rougeron and exposed in the open litterature by Moskalenko in 1982.

The relationship between the temperature T and the saturating vapour pressure p is given by the Clausius equation :

$$d\,(l_n p) / d\,(T^{-1}) = -\frac{\Delta H}{R}$$

where H is the latent heat of vaporization and R the universal gas constant.

This equation is represented by a straight line on the so-called Van't Hoff plot with $l_n p$ in ordinates and 1/T in abcissae. If the atmosphere of Venus is represented on the same diagram with the same coordinates, it is found that for a number of chemical compunds the saturation curve encounters the atmospheric variation at one point where the vapour will condensate. Below this point, the atmospheric density increases faster than that of the steam which becomes superheated.

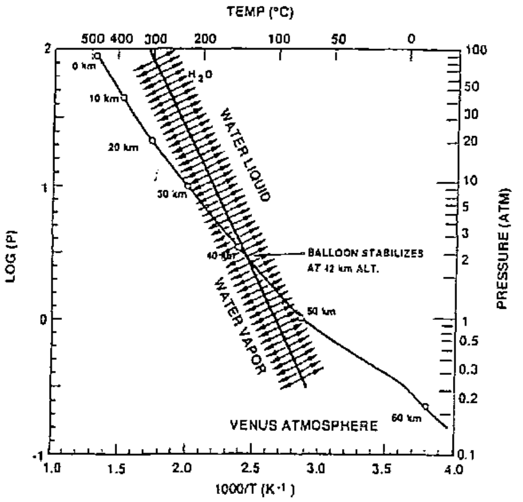

Fig. 2. Van't Hoff Plot of Water and Venus Atmosphere.

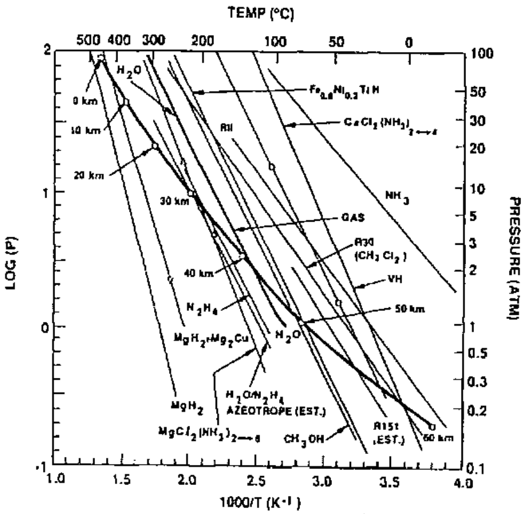

Fig. 3. Van't Hoff Plots for Reversible Fluids.

A very favourable case is provided by H_20 which condensates around 42 km. The net lift at this point is 2.10 kg m^{-3} of carrier gas. For CH_3OH, the condensation occurs at 51.8 km ; for the azeotrope H_20/N_2H_4 at 30 km.

The balloon will stabilize at the condensation altitude and oscillate around this altitude with a period and amplitude depending on the efficiency of the heat exchanges between the ambient and the filling gas.

Large oscillations between two fixed altitudes can be obtained with the use of two different gases filling separate or common vessels. Variants are possible :

1) Two vessels, each of them containing a condensing gas (exemple : H_20 and N_2H_4). The system will oscillate between 42 and 30 km.
2) Two vessels, one of them filled with H_20 and the other with a not condensable gas, as helium or hydrogen. The system will oscillate between 40 and 47 km ; with H_20

replaced by toluene, between 28 and 36 km ; by paraxylene around 17 km. Octane, cyclohexane and anisole (benzene-metoxy) have been studied by M. Romero and provide various altitudes of stabilization.

3) One vessel filled with a buoyant gas (H_2…) and the other equipped with a high pressure container where the gas will condensate and stay trapped with the help of a valve, for instance CH_2Cl_2 at 58 km. This system will allow large excursions and even reversible landings.

J. Jones and K. Nock at JPL have demonstrated the feasibility of the concept of reversible phase changes in balloon, using two separate vessels filled respectively with helium and Freon R-114, condensing in the Earth's atmosphere around the altitude of 5 to 7 km depending on the season. In the flight Alice O-D in 1994, they obtained five successive oscillations between 6 and 10 km of altitude, with a period of two hours.

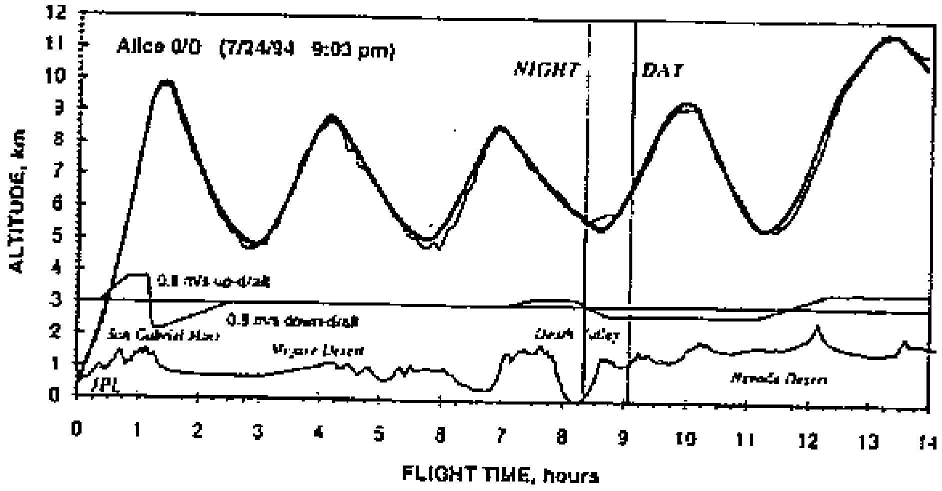

Figure 4. ALICE 0/D altitude vs time

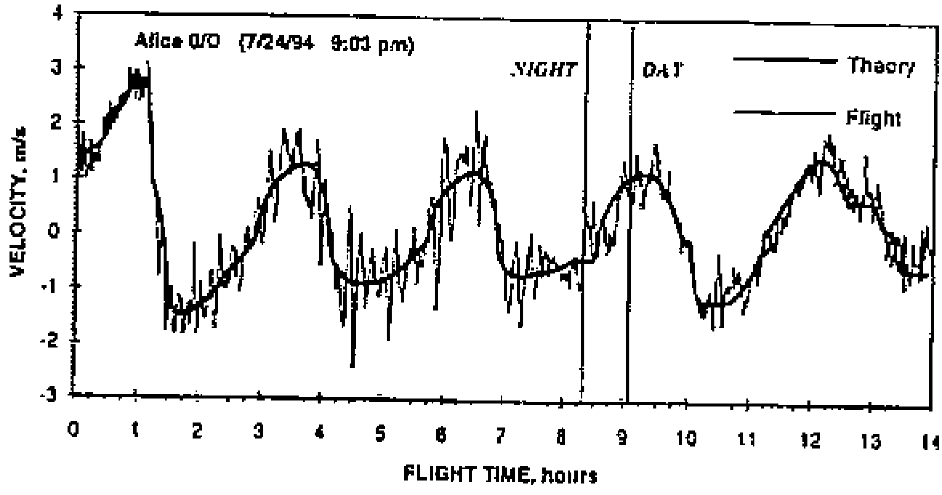

Figure 5. ALICE 0/D velocity vs time

In their BEV (Balloon Experiment at Venus) proposal, A. DiCicco, K. Nock and G. Powel show that a mixture of NH_3 and H_20 would provide stable oscillations between 40 and 60 km of altitude (3.4 bar, + 143°C and 0.2 bar, - 10°C). A single altitude cycle is estimated to take approximately 6 hours with 2/3 of the time spent ascending at a rate of 1.4 m/s and 1/3 of the time descending at a rate of 2.2 m/s. Mixtures H_20/ NH_3 open the possibility of varying the parameters, specially the top and bottom altitudes, by choosing the percentage of the two components. A 50/50 mixture would be 90 % condensed at 55 km ; with 12 % H_2O, it would begin condensate at 54 km and reach 60 km where 90 % of the was condensed. When H_20 is condensed, it can be collected in a lower, finned exchanger wherein H_20 will not evaporate until descent to the saturation altitude of 42 km.

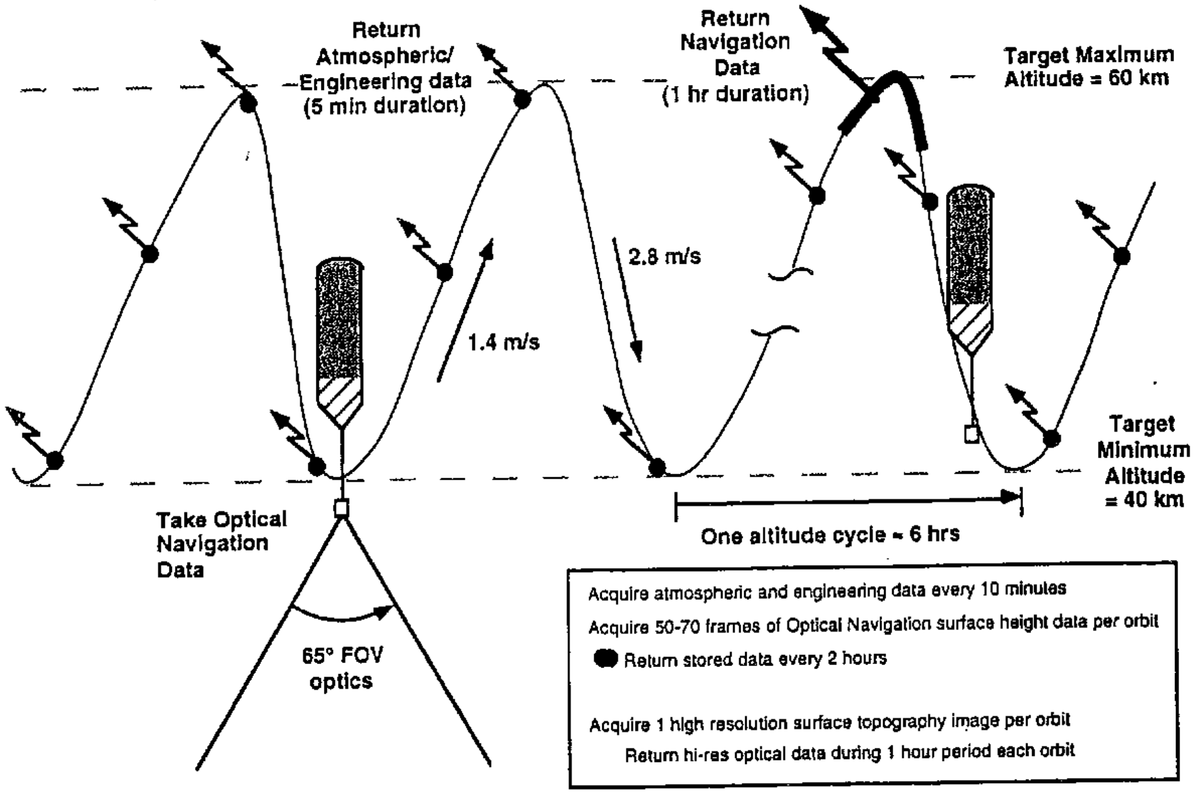

Figure 6 . Altitude Cycle Dynamics with Data Acquisition and Return Strategy

2) <u>The montgolfiere, or hot air balloon</u>

The montgolfiere is an open balloon, filled with ambient air. The buoyancy is provided by the difference of temperature between the atmosphere and the gas inside the balloon. Two sources of energy can be envisioned :

1) Solar radiation during the day. On Venus, the buoyancy is larger than 100 gm^{-3} from the ground level to 68 km altitude. With a skin density of 150 gm^{-2}, a 500 kg payload can be accommodated by a 7 000 m^3 balloon of total mass 700 kg floating at all altitudes from 50 km up to 68. The excursion is obtained with a valve placed at the top ; the bottom aperture has to be larger than 1 m^2. A small montgolfiere of 10^3 m^3

weighting 90 km will float at 66 km with a 30 kg payload. Exemple of application : jettisoning of a Vega style balloon 3.7 m diameter, for a total mass of 70 kg and 7 kg payload, including gas storage (43 kg) and inflation system (5 kg).

2) Infrared radiation added to solar, during day and night. The buoyancy during the night is 15 g m^{-3}. The top hemisphere of the balloon is made of aluminized mylar and the bottom hemisphere of polyethylene. A 500 kg payload would need a 60 x 10^{3} m^{3} volume which, if routively used by CNES on Earth, seems impossible on Venus. A more likely 4 000 m^{3} balloon of mass 34 kg would carry a (10- 6 kg) payload. The excursion would be reversible from 50 to 64 km.

Montgolfieres have advantages : they do not require carrier gas and they survive holes, creases or cracks in the fabric. However they have the major disadvantage of a weak buoyancy, which means a very large volume : therefore they carry a large mass of gas, and therefore should not be recomended for low altitudes Venus flights.

2 – TECHNOLOGY ISSUES

1) The balloon fabric

Two types of materials can be envisioned :

(a) **Polymers.** The use of aluminium-coated kapton with polyimides as adhesives is considered a serious option, as the most thermally stable material up to 350°C with brief incursions to 410°C, needing no developments.

Yavrouian, Yen, Platt and Weissman at JPL (1995) consider as the leading candidate PBO (polybenzoxazole) developed by Dow Chemical. This polymer has no melting point nor glass transition temperature. Foster Miller is currently capable of producing axially oriented PBO films in 50 x 90 cm sheets up to 25 micron thickness. Tensile strength and modulus, tear resistance, permeability and UV resistance, good at room temperature, tested by the JPL Group, have experienced no degradation at 500°C, without loss weight, during 6 hours. The density of 1.54 g cm^{-3} is similar to kapton's (1.42).
PIBO, a film forming PBO copolymer, soluble in organic solvents, has been identified as a candidate sealing material. Its properties at high temperature are comparable to those of PBO, and it can be applied on the fabric with a commercial coater.

(b) **Metallic enveloppes**. In 1980 M. Rougeron and myself at CNES fabricated an aluminum balloon. Aluminum foil is a candidate up to temperature of 200°C (altitudes above 33 km) since at higher values, the material loses its strength. Titannium sheet (density 4.6) seems a more promising candidate. It is standard manufactured in thicknesses of multiples of 25 microns. Tensile strength is up to 600 MPa at 500 °C.

Sheets would be electrically welded. The balloon could be given the shape of an accordion (Chinese lantern) or of a tetrahedron, currently used by CNES because of its property of developpability on a plane, enabling the fabrication by continuous welding from a sheet. For example, since the surface area and volume of a tetrahedron of edge L are respectively $A = 1.732\ L^2$ and $V = 0.1179\ L^{3,}$ a 1 m^{3} balloon will be obtained with a tetrahedron of edge length 2.040 m and surface area 7.206 m^2. With a balloon aluminum fabric 0.05 mm thick of mass 0.969 kg, the payload permitted would be 1.15 kg at 42 km altitude with H_20 as buoyant gaz. The balloon is limp, not taut or superpressurized.

Resistance to $H_2\ SO_4$ would be obtained, for aluminum by anodization or PTFE (polymery tetrafluorethylene) coating, stable up to 325°C, or for titanium, by the use of improved resistance alloys.

2) Gas filling

The stabilizing fluids would be transported as liquids in plastic bottles. The bottles, of very low mass, would melt at high temperature and release the gas inside the balloon. Another solution is gas/solid chemisorption : for instance $CaCl_2(NH_3)x$ releases NH_3 at the altitude of 57 km.

Hydrogen could be stored as hydride $LiAlH_4$, which decomposes at 50 km altitude (it can be seen that 37 gm produce 2 moles of H_2). The solid products of decomposition could be jettisoned.

High pressure vessels collecting the liquid when it condensates provide reversible excursions.

It has to be realized that Venus balloons at low altitude would be rather small.

3) Power

(1) **Batteries :** several mature options exist for batteries operating at high temperatures :

- lithium iron disulphide, between 350 and 550° C,
- sodium sulphide, between 220 and 360 °C.

They are precharged in the molten stage, and cooled for storage. Their energy capacity, theoretically 500 to 750 Wh/kg should be realistically estimated around 100 Wh/kg.

(2) **Power sources** : at high altitudes (55 km) a solar generator of triple junction amorphous silicon cells receives an available solar power of 40 W/m^2 for a SZA of 45°. It is not expected they could function at low altitudes.

For altitudes below 55 km, RTG offer the only solution, but they need insolation and cooling since they generate heat (50 W/kg). It is not possible to provide a figure of merite, but we can quote as systems possible but deserving development :

- Pu-238 space qualibred "power stick", mass 0.3 kg, power density 0.13 W/kg, energy density $>10^4$ Wh/kg,
- RTG "Angel" developed for Mars 96, mass 0.5 kg, power density 0.44 W/kg, energy density $> 4 \times 10^4$ Wh/kg

4) Electronics

Simple electronics are commercially available for functioning up to 225°C (altitude 25 km).

Higher temperature requires dedicated development. Available technologies are :

- SOI (up to 300°C) : MOSFET devices reasonably mature,
- Ga As or Ga N (up to 450°C) : FET reasonably mature,

- SiC (up to 350-650°C) : MOSFET, FET and transistors ; only transistor technology suitable for high temperature. Simple integrated devices exist,
- Solid state vacuum devices (up to 1 000°C) : transistor FET like function, exist at low integration level,
- vacuum tubes : a transmitter using vacuum tubes was developed at JPL in 1982 as a demonstration for a Venus high altitude mission. Its design used a ceramic planar-triode transmitting tube coupled to a cavity as a feed back oscillator.

5) Active cooling

NASA has developed a 1.6 kg Stirling cooler with a cooling capacity of 100 W over a temperature gradient of 250°C (input power 240 W). Together with a RTG heat source, the mass becomes 21.6 kg. With this system, the temperature of the electronics is still high below 21 km.

3 – SCENARIO

1) Study of the general circulation

This study would be entrusted essentially to the tracking of 24 passive Lagrangian tracers carrying only a metallic reflector (for instance their skin) and localized by a Doppler radar placed on the satellite. A polar orbit provides the possibility of localizing once per Earth day balloons situated anywhere on one hemisphere of the planet.
Balloons would be distributed at a variety of altitudes, latitudes and longitudes

Altitude 18 km (n = 20 bars, T = 350°C)

9 floatters, each comprising one H_2O balloon and one anisole (or paraxylene) balloon.

	R^{cm3}	V^{m3}	M_1^{kg}	M_2^{kg}	M^{kg} Total fluid	M^{kg} A(liq)	M^{kg} A(vap)
H_2O	42.5	0.32	0.16	1.00	3.15		
anisole	20.5	0.034	0.036	0.23	2.65	1.32	1.32

M_1 = balloon mass for kapton of 50 micron thickness

M_2 = balloon mass for titanium of 100 micron thickness

The total mass of the system is 6 kg (for the kapton option) or 7 kg (for the titanium option), compared to the free lift of 8 kg providing if needed a 1 to 2 kg payload.

Altitude 30 km (n = 10 bars, T = 220°C)

5 floatters, each made of one balloon with (N_2H_4 – H_2O) azeotrope.
The 0.864 m^3 balloon (radius R = 60 cm) contains 5.25 kg of azeotrope and weights 2 kg (titanium 100 microns) or 0,3 kg (kapton 50 microns) with a 4 kg total free lift.

Altitude 42 km (n = 2 bars, T = 150°C)

5 floatters, each made of one balloon inflated with 2 kg of H_2O. We have seen that a 1 m^3 tetrahedron, with a mass enveloppe of 1 kg could carry a payload of 1.15 kg (not required here).

Altitude 50 to 60 km

A number of solutions can be found for the 5 floatters at this level. CH_3OH would provide stabilization at 52 km (p = 1 barr, T = 70°C), or a combination of H_2O an NH_3, or the more exotic use of the compound $CaCl_2(NH_3)_x$ which releases NH_3 vapour at 57 km (p = 0.2 barr, T = 0°C), or even helium following the solution chosen for the Vega balloon.

In the case of CH_3OH a 2 m^3 balloon would carry 500 gm of methanol. The skin mass would be 500 gm for 50 microns polyethylene.

The total mass of the 24 balloons is therefore : 9 x 6 + 6 x 5 + 3 x 5 + 3 x 5 = 114 kg

Supposing the release by a 45 kg entry vehicule carrying 45 kg of deliverable, the 24 balloons would have to be regrouped in 3 packages (8 balloons for each entry vehicle : 3, 2, 1, 1) for a total mass of 250 kg.

2) Study of the chemistry

The major feature would be the use of a high performance chemical analyzer (not defined in this paper) which could be a GCMS or a laser diode device. This instrument (CA), to be developed, would be refrigerated by an active cooling device. It is the heart of the mission and would receive top priority in the list of instruments. Its mass would be limited to 2 kg plus 2 kg for the cooler.

a) In the cloud region (see figure 6)

The aerostat would be a 4 meter diameter balloon of 5 kg mass, made of coated PBO, inflated with a mixture of H_2O and NH_3 released on board from liquid or mixed solid phases. It would oscillate between 40 and 60 km within a cycle of about 6 hours, carrying 25 kg of lifting fluid and a 18 kg gondola. The power for the Stirling cooler would be provided by solar cells and batteries. Total mass including entry and deployment systems is estimated around 100 kg.

b) In the low altitude region

The low altitude balloon hovering near the surface is the most challenging part of the mission. It is a titanium balloon, radius 60 cm, mass 2 kg, carrying 25 kg of H_2O. It can lift a 33 kg payload including the CA as unique science instrument, cooled at all times by a vacuum tube transmitter. Mass of the package is 70 kg, to be delivered by a 45 kg entry system for a total budget of 115 kg. Adding an ascending system using methylene chloride on an auxiliary balloon is an exciting option for cooling at high altitude.

c) Mixed dynamics and chemistry

The balloon described in the ESA Technology Reference Study (SCI-AP/2006/173/VEP/MvdB) by Marcel Van den Berg and Peter Falkner complement the above described mission by providing measurements of the atmosphere including a GCMS performed on board a balloon of classical design (H_2 inflated) of 4 m diameter, and 15 atmospheric microprobes for a 4.40 kg mass). Total mass for entry vehicle and balloon system is estimated at 91.1 kg.

4 - ACCOMODATION

The overall mass budget amounts to :

- 60 balloons	250
- chemistry : cloud region	100
- chemistry : low altitude	115
- mixed dynamics	90
TOTAL	555 kg

The ESA Reference Study considers the mission as launched by a Soyouz-Fregat 2-1b from the CSG with a total mass capacity of 1509 kg. The polar orbiter accounts for 905 kg and the excentric orbiter for 558. The present proposal to exchange the excentric orbiter for a fleet of 27 balloons is therefore compatible with the overall mass constraints. It is understood that the project would require a 20 % margin which at this early stage, has not been taken into account for some parts of the the balloon fleet design presented here. The margin could obviously be obtained by the suppression of one of the balloon systems ; however, it is hoped that further study will provide the margins.

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J. BLAMONT

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