[5] Florio, F. A. and Hobbs, R. B., "An Analytical Representation of Temperature Distributions in Gravity-Gradient Rods," *AIAA Journal*, Vol. 6, No. 1, Jan. 1968, pp. 99–102.

[6] Love, A. E. H., *The Mathematical Theory of Elasticity*, Dover, New York, 1944.

[7] Landau, L. D. and Lifschitz, E. M., *Theory of Elasticity*, Addison-Wesley, Reading, Mass., 1959.

[8] Predmore, R., Staugaitis, C., and Jellison, "Damping Behavior of DeHavilland Stem Booms," TN D-3996, June 1967, NASA.

[9] Boley, B. A., "Thermally Induced Vibrations of Beams," *Journal of the Aeronautical Sciences*, Vol. 23, No. 2, Feb. 1956, pp. 179–181.

[10] Jordan, P. F., "Observations on the Mechanisms of Thermal Torque Instability" *ASME/AIAA 10th Structures, Structural Dynamics and Materials Conference*, AIAA, New York, 1969.

[11] Mindlin, R. D. and Goodman, L. E., "Beam Vibration with Time-Varying Boundary Conditions," *Journal of Applied Mechanics*, Vol. 17, Dec. 1950, pp. 377–380.

[12] Predmore, R. E. and Staugaitis, C. L., private communications, Feb. 1969.

[13] Frisch, H. P., "Coupled Thermally Induced Transverse Plus Torsional Vibrations of a Thin-Walled Cylinder of Open Section," TR R-333, March 1970, NASA.

AUGUST 1970 J. SPACECRAFT VOL. 7, NO. 8

Buoyant Venus Station Requirements

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Use of a Buoyant Venus Station, a balloon-supported instrument package, to explore in the atmosphere of Venus would permit instruments to operate in a moderate environment with advantages of long duration in the atmosphere and mobility. Measurements relating to atmosphere and surface could be made, the latter either indirectly or by sondes dropped from the station. The concept is not sensitive to the choice of companion spacecraft mission mode; with minor differences, a station weighing 500 lb at deployment is suitable for flyby, orbital, and swingby missions. This paper describes three technologies requiring development: heat shield, superpressure balloon, and tracking of the station to determine position. A modest development program is proposed.

Nomenclature

A	= area, ft²
B	= ballistic coefficient, slug/ft²
C	= coefficient, nondimensional
DSIF	= Deep Space Information Facility
DSN	= Deep Space Network
h	= height, ft
M	= Mach number, dimensionless
$\dot{q}$	= heating rate, Btu/ft²-sec
q	= dynamic pressure, lb/ft²
r	= radius, ft
SE	= sub-Earth point, dimensionless
SWR	= Southwestern Research Corporation
t	= Time, sec
T	= Temperature, °R
UHF	= ultra-high frequency, dimensionless
v	= velocity, fps
V	= volume, ft³
ρ	= density, lb/ft³

Subscripts

B	= balloon
D	= drag
E	= entry

Presented as Paper 69-1068 at the AIAA 6th Annual Meeting and Technical Display, Anaheim, Calif., October 20–24, 1969; submitted November 3, 1969; revision received March 26, 1970. Work supported by NASA under Contracts NAS1-6607 and NAS1-7590.

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Introduction

THE use of a buoyant station[1,2] to explore in the atmosphere of Venus has been under study since 1966. By drifting with the prevailing winds for periods of one week to possibly several months, this vehicle could answer many scientific questions that cannot be easily answered by any other type vehicle such as a ballistic probe. What is the atmospheric circulation pattern and the mechanism driving it? What is the composition and structure of those mysterious clouds? What are the trace elements in the predominant CO_2 atmosphere? What is the structure of the clouds? What is the general topography of the surface (determined by mapping from the station)? The Buoyant Venus Station (BVS) permits instruments to be supported in the atmosphere in a moderate environment with the additional advantages of long-duration survival and mobility over the surface generated by existing winds. A typical complement of instruments would include radar altimeter, pressure, and temperature transducers, photometers, water vapor detector, accelerometers, mass spectrometer/gas chromatograph, and possibly some simple life-detection equipment. A cable suspended from the station supports the temperature and water vapor instruments. The below-station atmosphere is sensed by drop sondes, which relay their data to the station. The drifting station may either relay its data to a companion orbiting spacecraft or directly to Earth. Balloon technology, though adequate for Earth-launched balloons, requires further development for this application. The ability to track the station as it moves across the planet surface appears to present measurement technique and accuracy problems. Studies are being conducted on balloon-based

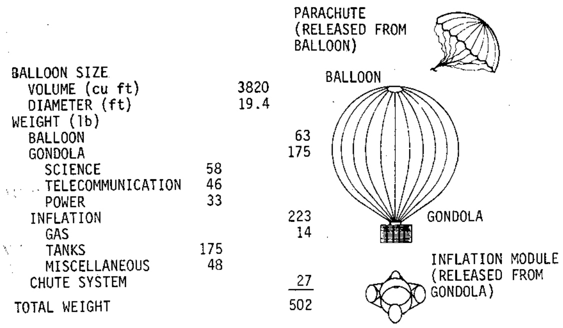

Fig. 1 Typical BVS parameters.

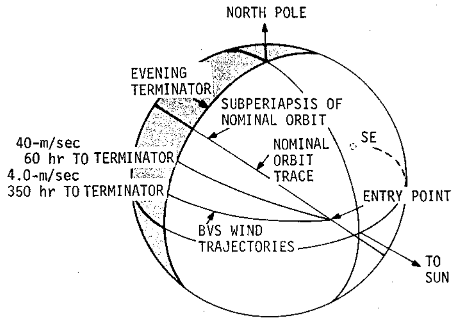

Fig. 3 BVS wind trajectories, orbiter mission.

sensors, orbiter-supported measurements, Earth-based tracking, and combinations thereof. This station is designed to float at a given density in the atmosphere. For the early BVS, it was decided that the station should float in a well-defined region of the atmosphere, based on Mariner V occultations and Venera IV and V data, and yet within the clouds that are of great interest. The top of the clouds are assumed to be nominally at 70–75 km above the reference surface of 6050 km. Therefore, this BVS, floating at 58 km, is well within the clouds. The BVS will seek and float at the design density (0.066 lb/ft^3). Therefore, if the actual atmosphere has a lower density, the station will float at a correspondingly lower altitude with slight differences in the pressure and temperature. This is not a problem within the accuracies assumed for the Venera and Mariner occultation data.

The BVS concept is insensitive to the interplanetary spacecraft mission mode selected. With minor differences, a station (Fig. 1), weighing approximately 500 lb at deployment is appropriate for flyby, orbital, and swingby missions. The 175-lb gondola has a 58-lb science instrument complement in addition to its communication equipment including a 20-w UHF or S-band transmitter, antenna, power supplied from batteries, and a solar array mounted on the surface of the gondola. The balloon is a superpressure design, inflated with hydrogen gas, supporting the gondola.

Three mission modes studied for the BVS, delivered in each case by a Mariner-class spacecraft to the planet, are 1) Titan IIIC for a flyby mission, 2) Titan IIIC launch for an orbital mission, and 3) a Venus/Mercury swingby mission, which requires a Titan III with a high-energy upper stage. A large range of atmosphere entry velocities, 32,000–44,000 fps, results from these mission modes. In comparison, the Mars direct entry velocity is 20,000 fps or less.

From entry through flotation of the BVS the missions are generally similar, as illustrated in Fig. 2. BVS staging takes place at the time the capsule has reached subsonic velocity, e.g., $M = 0.5$. A parachute, deployed by a mortar, extracts the afterbody that extends the main parachute, a 35-ft-diam disc-gap-band, and falls away with a break tie. The parachute provides a dynamic pressure flowfield of approximately 1.0 psf for the extraction and inflation of the balloon, initiated by barometric pressure sensing. All subsequent deployment events are timer-initiated. The balloon is inflated by high-pressure hydrogen gas released, unregulated, into the extended balloon. After inflation the tanks are dropped. Excess gas is injected to ensure reversal of the downward velocity of the station. Equilibrium flotation resulting after warming of the cold hydrogen gas occurs some 30 min after entry.

The BVS horizontal mobility is expected to be a direct function of the wind pattern. Model wind patterns have been generated[3] for our studies based on observed and theoretical data. Generally, investigators[4] agree that the circulation is mainly along the meridional direction from near the subsolar point, which is absorbing solar energy to near the antisolar point, which is radiating to space. The model assumes that Venus is slowly rotating, thereby altering the simple meridional flow. Wind patterns for the expected range of wind velocities from 4–40 m/sec have been generated. For a typical orbital mission with a wind velocity of 40 m/sec, the BVS time on the light side can be expected to be 60 hr and as long as 350 hr for 4-m/sec winds (Fig. 3). For this mission the BVS remains near the plane of orbit for relay communications to the companion spacecraft. The BVS entry for flyby and the Venus/Mercury swingby missions would be targeted near sub-Earth for a direct-Earth communication link. Typically the BVS light side duration for a flyby mission can be expected to be 17 hr and as long as 100 hr, depending on the wind velocity. The swingby mission requires the BVS to enter on the dark side of the planet and drift with the winds on that side.

Heat Shield

The entry environment resulting from the range of entry options just described is an important consideration for any Venus atmospheric probe mission because of the expected aerodynamic heating and large deceleration pulse. The deceleration resulting from entry velocities of 32,000 to 44,000 fps are from 170–360 times Earth gravity (Fig. 4). This deceleration magnitude is a manageable problem based on electronics packaging techniques developed at Martin

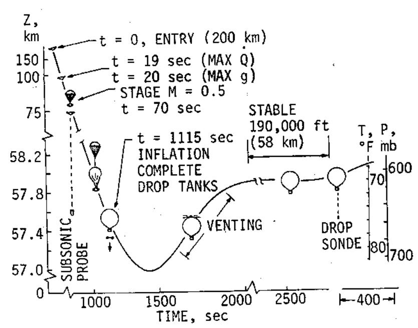

Fig. 2 Entry and deployment sequence.

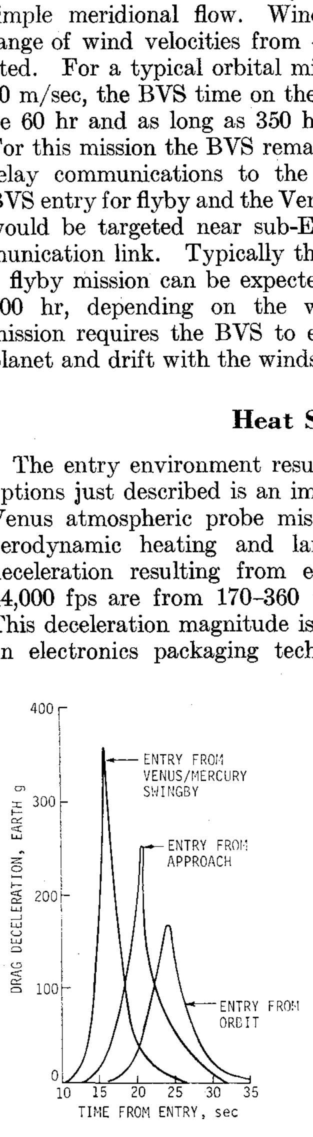

Fig. 4 Entry drag deceleration.

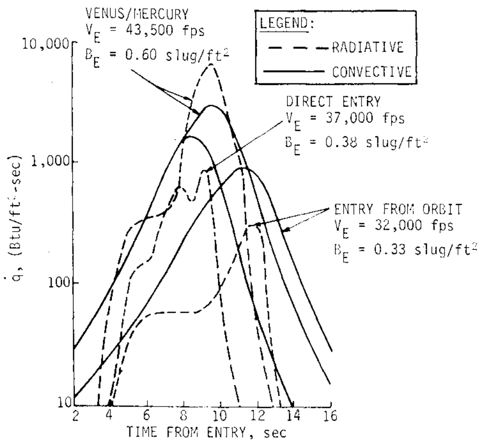

Fig. 5 Entry aerodynamic heating (30° entry angle).

Marietta Corporation and confirmed by test. These packaging techniques allowed the equipment to operate successfully following accelerations up to 500 times Earth gravity.

The resultant aerodynamic heating from the above missions is shown in Fig. 5. Although wide variations in entry conditions are involved in the various Venus mission modes, it appears that essentially state-of-the-art ablative material systems can provide the required protection for the aeroshell structure for all the above missions. One of these materials, carbon phenolic, appears capable of providing protection for even the Venus/Mercury mission; however, other materials may be more desirable for the direct and orbital entries because of their lower density (lower heat shield weight) and their nonrigid nature (elimination of thermal stress considerations). In particular, a modified version of a state-of-the-art carbon-reinforced elastomeric silicone material is recommended for the direct and orbital entries.

In spite of the background of Earth entry and ground testing for several of the candidate materials shown in Table 1, all require some degree of fabrication development to adapt them to shallow cone aeroshell configuration and to the sterilization and decontamination procedures. In addition, more ablation tests are required on these materials to characterize their performance in the Venus entry environment due to differences in the Venus and Earth entry conditions and aeroshell configuration. The greater density gradient of the Venus atmosphere and its CO_2 rich composition combine to produce: 1) higher levels of radiation heating than comparable velocity Earth entries; 2) significant radiation in the UV wavelengths; 3) CO_2-char reactions; and 4) high surface shear levels over a large area of the vehicle.

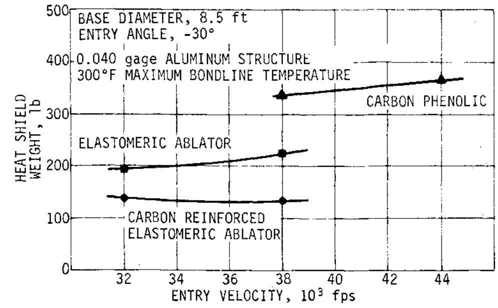

Fig. 6 Heat shield weight sensitivity.

The heat shield analyses of this study have accounted for the preceding factors in a conservative fashion and the resulting weights (Fig. 6) have been found to be compatible with mission requirements. The degree of completeness with which test programs can be accomplished to confirm these analyses decreases with increasing entry velocity as seen in Fig. 7. This results in an increased dependence on analysis and, consequently, an increased though still acceptable risk level associated with the designs for the extreme velocity, Venus/Mercury swingby mission.

Heat Shield Development

The steps in a heat shield development program are summarized below.

Small models of several candidate materials would be exposed to selected levels of combined radiative and convective heating in radiation-supplemented plasma arc heat sources; to shear forces at high temperatures in pipe flow tests (plasma arc facility), and to "splash" tests in a CO_2-operated plasma arc to obtain comparative ablation performance and to establish a mathematical ablation model for the various mechanisms of material degradation involved. After material candidates are narrowed to one or two, additional tests would be conducted to verify the mathematical ablation model by comparison of test and analysis results. A third phase would completely characterize the selected material by in-depth testing at test points corresponding to critical conditions in the anticipated mission profile. Finally, thermal-structural verification tests would be conducted on large-scale parts of the aeroshell with the heat shield installed. Facilities for the latter tests would depend on final heat shield design and might include use of large-nozzle

Table 1 Heat shield materials

High density 90 to 110 lb/ft³		Low to intermediate density 30 to 60 lb/ft³							Super low density 15 lb/ft³	
Rigid		Rigid		Elastomeric				Carbon reinforced elastomeric	Elastomeric	
Carbon phenolic	Silica phenolic	30 lb/ft³ filled epoxy Avcoat 5026—39 HCG	30 lb/ft³ nylon phenolic	30 lb/ft³ purple blend	30 lb/ft³ DC 325	30 lb/ft³ ESA 3560	55 lb/ft³ ESA 5500	60 lb/ft³ ESA 5500M	ESM 1004X	SLA 561
Ballistic missiles	Ballistic missiles	Apollo	Scout re-entry series	Scout re-entry series	Gemini	PRIME	PRIME	Development	Mars	Mars
Rigid nature causes thermal stress	More recession than carbon phenolic due to melting silica. Also less heat reradiation.	Better insulation characteristics are offset by lower resistance to mechanical erosion. Also the rigid materials introduce thermal stress problems.						Good insulation and flexibility maintained Erosion reduced markedly	Extreme recession rates. (Not applicable for reference mission.)	
Low recession, significant thickness still required due to high thermal conductivity										

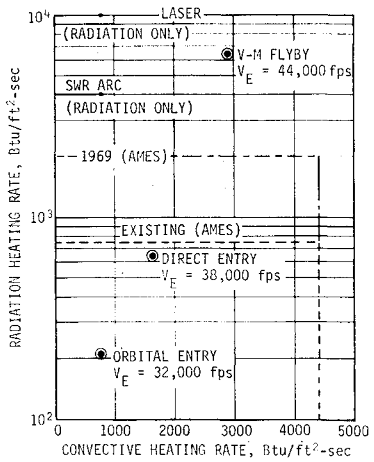

Fig. 7 Entry heating simulation.

plasma arcs, or banks of resistance heater elements. Concurrent with the early phases of the program would be material and fabrication process development, and exposure of materials to the preentry environmental aspects of the mission.

Corollary to the material development is a program required to confirm the predictive methods for radiative heat transfer to the vehicle surface from the shock layer gases. At present, little shock tube data are available for CO_2 gas mixtures for nonequilibrium conditions. Also, the question of the influence of absorption of radiant energy by ablative products has not yet been resolved. An experimental program to substantiate radiation heating methods should reduce the relatively large tolerances on heating currently used in this study.

Simulation Requirements

In the small ablation model tests, the key requirements are achieving surface temperatures (in the carbon sublimation range), and inducing proper viscous shear forces in conjunction with these surface temperatures. Radiant heat inputs are important in bringing the surface up to the correct temperature but are not believed to introduce a unique degradation process. Based on the best analysis available, even the ultraviolet wavelengths, which are not attainable in existing test facilities, are expected to result simply in absorption of energy at the surface in the form of heat.

In the large-scale thermal-structural tests it is more difficult to establish criteria for simulation. However, it is believed that a test would be satisfactory that brings the heat shield surface up to the temperature at which the ablator's elastic modulus and strength become negligible. For the materials that remain rigid at high temperatures, e.g., carbon phenolic, this could require the development of an improved test capability, whereas, for the flexible elastomers existing heat lamps are adequate.

Earth re-entry flights (at steeper entry angles) have been analyzed[5] and found to offer some interesting possibilities as proof tests, but no present requirement has been established justifying the expense of flight tests.

Several potential heat-protection concepts appear workable for Venus entry with two of the leading candidates being carbon phenolic and carbon reinforced elastomeric silicone; the carbon reinforced elastomeric silicone material yielding a more desirable weight fraction. Both require additional development and a systematic test program to adapt and qualify them for Venus applications. Also, further experimental work is indicated in confirming aerodynamic heating prediction methods.

BVS Balloon

The requirements of the deployed superpressure Venus balloon are understood from extensive Earth balloon experience. The National Center for Atmospheric Research (NCAR) has been successfully launching and tracking superpressure balloons for more than two years as part of their Global Horizontal Sounding Technique (GHOST) program over the southern hemisphere. Some of these Mylar balloons have survived for more than one year. However, these launches and practically all experience to date is limited to the slow, convenient operations of site delivery and deployment. The Earth-launched balloons can be checked, tested, and made flight-ready at the time of launch, and the balloons can be launched when the atmospheric conditions are most favorable. Design and fabrication of the Venus balloon is complicated by the requirements of packing, sterilization, the loading experienced during atmospheric entry, and the extraction and deployment under aerodynamic loads. The balloon requirements for a Venus mission are 1) design for superpressure sufficient for environmental variations; 2) pressure relief systems will be provided; 3) balloon shall not allow more than 4×10^{-10} std ft³/sec/ft² of hydrogen permeation at design differential; 4) design to operate 168 hr minimum; 5) deploy and inflate, within 45 sec, with external dynamic pressure of 1.0 lb/ft²; 6) a single point attachment shall be used at the balloon apex; 7) the diffuser sock shall support the gondola free-fall shock load; and 8) the balloon shall be packed in a minimum volume.

These additional, mission-peculiar environments, as shown in Fig. 8, require development of design and fabrication techniques.

Balloon Deployment

The BVS balloon deployment sequence begins with sensing the proper atmospheric pressure (typically 612 mb), while the BVS is descending on a parachute. This triggers ordnance devices that release the balloon storage canister lid allowing the gondola and inflation tankage to fall, thus extending the folded balloon. When the balloon is fully extended, ordnance valving is opened and the high-pressure hydrogen gas rapidly inflates the balloon, typically in 45 sec. The depleted tanks and parachute are then jettisoned and the station seeks equilibrium flotation.

The extension of the balloon produces a load on the balloon because of the free fall of the gondola/inflation tanks. This

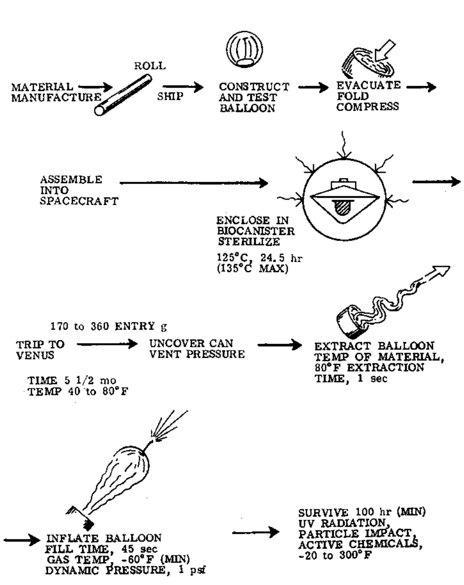

Fig. 8 BVS balloon environments.

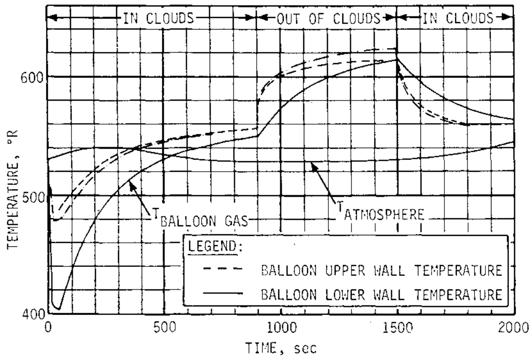

Fig. 9 Temperature variations in and out of clouds.

shock load should not be carried through the balloon skin. The 1.0-psf flowfield produces flutter loading on the balloon skin during the inflation until a significant bubble is realized with the inflation gas.

The feasibility of performing these deployment and inflation operations was sought, and this prompted NASA to undertake a test program. Deployment and inflation tests were successfully performed in the Langley Research Center Full-Scale Wind Tunnel using two balloons fabricated by only commercial practices. This type balloon has also been statically inflated several times at our facility with hydrogen gas in 45 sec. However, these test balloons were not decontaminated, heat sterilized, or packed and subjected to long-term storage before test.

Balloon Flotation

A superpressure balloon is, for all practical purposes, a constant atmospheric density device. It is a nonextensible balloon that is sealed to prevent gas release; its internal pressure exceeds local ambient. Fluctuations of balloon gas temperature with attendant gas pressure excursions will cause the balloon volume to vary in accordance with the balloon material modulus. Because negligible gas mass is lost from the system due to venting, the balloon will seek essentially the same constant density altitude.

The problem of floating in and out of the clouds of Venus has been analyzed to determine this effect on balloon gas temperature. Figure 9 shows the initial balloon inflation and near-equilibrium recovery while in the clouds. The thermal environment is then changed by drifting out of the clouds. Thus, the balloon is in direct sunlight and the radiant energy increases the gas bulk temperature above local ambient. This temperature differential is referred to as "supertemperature." This creates an increase in the gas pressure and causes either an increase in the stress level in the balloon material or requires that some gas must be vented overboard to maintain a constant superpressure. Again the station drifts into the clouds (similar to crossing the terminator) and the gas is cooled, reducing the superpressure. Thus, two potential problems must be overcome. First, the balloon material optical properties play a major role in the gas temperature fluctuations. With the right choice of properties, these fluctuations can be minimized. Second, the balloon material strength determines whether gas must be vented overboard. Each time gas is vented there is a reduction in the number of future cycles in and out of the clouds which the balloon can accommodate, thus limiting mission life.

Another effect that must be considered is vertical winds in a turbulent atmosphere. The effect of downward winds is not of concern because a superpressure balloon has an inherent restoring force that increases with displacement below its equilibrium altitude density. Once the downward force is removed the balloon returns to its original state. However, updrafts are of concern to a balloon. As shown in Fig. 10, the upward displacement is a function of the force of the updraft. Along with this displacement is a noticeable decrease in atmospheric pressure, or conversely, an increase in superpressure. Again, if the balloon material strength does not allow for this resulting stress, some gas must be vented.

Balloon Development

Thus, additional development is necessary before a highly reliable, rugged balloon, capable of reliably performing this mission, can be designed and fabricated.

The materials screening test program[6] has been completed. The general approach to this test program was to evaluate various materials against the simulated Venus mission environments and requirements. The initial effort used some of the environments to screen out unsuitable materials, and the detailed test effort provided more refined environmental screening of four of the most promising materials. Selected critical environments were simulated based on the mission sequence. These simulated environments included handling and manufacturing abuse, packing, sterilization, long-term storage, high-g entry loading, deployment abuse, and UV exposure. The properties tests that were evaluated included tensile strength, tear strength, leak tests, interlayer sticking, and dimensional stability evaluation. The abuse devices used in the test program were designed to provide a relative measure of material ruggedness and leak resistance although these abuses were considerably more severe than any expected from handling, packing, and deployment of the balloon.

Test results showed that single films do receive pinhole damage if subjected to certain types of abuse and that bilaminates of these films do effectively control pinholing as was expected. The testing provided a relative ruggedness comparison for the various materials that was not previously available. Scrims and fabrics demonstrated a much higher strength-to-weight ratio than the films alone and provided a rugged ripstop character to the outer surface of the material. There was evidence of damage to varying degrees on all materials because of the environmental exposures; however, certain materials proved superior for the balloon application.

Further material investigation is required with special attention devoted to fabrication techniques. Also, packing of the balloon should be further investigated to minimize material creasing and stresses while packed and to minimize material loads during the balloon extraction process.

Position Determination

The problem of tracking the BVS and determining its position in Venus coordinates is unique in that the BVS is driven by the winds and most probably will not move along a prescribed trajectory as does a planetary orbiter. Thus, tracking systems generally applicable to orbiting spacecraft may only have limited applicability or not be applicable to BVS tracking. Further, the measurement of gross wind patterns and velocities is in itself an important scientific goal,

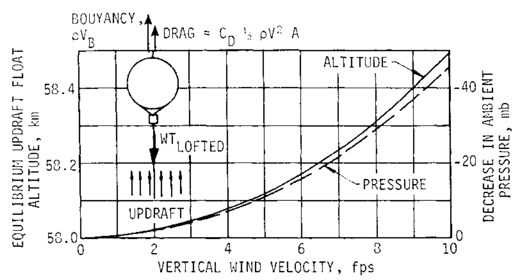

Fig. 10 Effects of updraft on performance.

Table 2 BVS position determination requirements

Position determination accuracies: 1000 km—useful; 500 km—better; 100 km—very good
Venus diameter: ~12,100 km
Venus subtended angle: ~33 sec of arc
Velocity determination accuracies: 1–2 m/sec horizontal and 0.1–0.2 m/sec vertical
Science measurement accuracies (temperature, pressure, density, composition):

BVS position	Absolute accuracy	Realtive accuracy
Latitude and longitude	1° (105 km)	0.01 to 0.02° (1 to 2 km)
Altitude[a]	1 km (h = 60 km)	...

[a] Prefer distance to center of planet to within 1 km.

while such an output would certainly add to the utility of any tracking and position determination system. Several implementation concepts have been investigated.[7] To date, no single system investigated is considered an optimum solution to the position determination problem; a variety of data derived from multiple sources may ultimately be the proposed technique to locate the BVS.

In studying various tracking systems it was necessary to develop a rationale for the accuracies desired. Considering a basic purpose of the BVS to be that of "mapping" atmospheric and surface observables, individual measurements were examined to formulate the requirements of Table 2. The absolute accuracy for the atmospheric measurements based on a Venus-centered coordinate system that will locate the BVS on a sphere, should be about 1° in latitude and 1° in longitude or about 100 km. The relative accuracy, on the other hand, should be about two orders of magnitude better for these measurements or about 1 to 2 km. It is this relative accuracy, the successive determination of position each sampling period, that is used to derive the observed wind velocity vector. These position accuracies may be considered too stringent for a practical BVS mission, but, nevertheless, scientific considerations alone dictate the desirability of achieving these accuracies. The particle size, distribution, and composition of the clouds should be measured to a sufficient accuracy to allow the data to be averaged over a 1 km^3 volume, which should be compatible with the design of an onboard microwave cloud sensor. The measurement of water vapor content of the clouds as well as the atmospheric attenuation measurement, must be correlated with the actual cloud motion to determine the extent of the clouds in three dimensions. Therefore, accuracies of 1° in latitude and 1° in longitude would be a minimum requirement for these measurements. Wind velocity data will be required for all of these measurements to establish circulation patterns

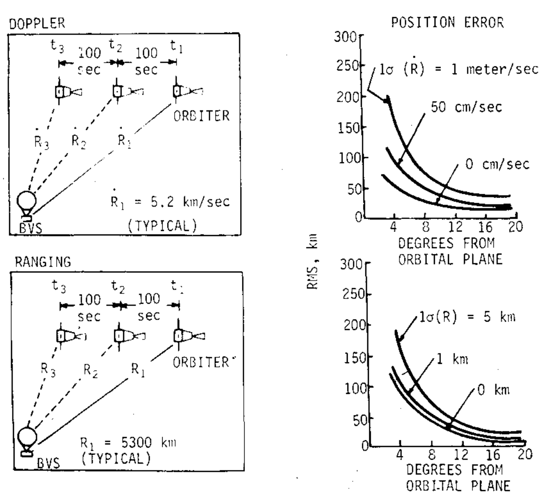

Fig. 11 Position determination, with orbiter.

in the Venus atmosphere. Doppler measurements using ground-based equipment will yield only the Earth-directed component of the horizontal wind velocity. Therefore, an onboard radar must be employed to obtain wind velocity measurements in Venus coordinates. These wind velocity measurements should be performed to an accuracy of 1 to 2 m/sec in the horizontal direction while the accuracy of the vertical wind component measurement should be 0.1 to 0.2 m/sec.

Considering the Earth-based measurements, it is entirely feasible to measure the Earth-directed component of the horizontal wind with the DSIF by performing Doppler measurements. A coherent transponder onboard the BVS will be required to obtain Doppler data, and the major problem encountered with this measurement will be random motions of the gondola that may affect the phase coherence of the transponder signal. Also CW radar systems will exhibit range and Doppler ambiguities because the target range repeats itself every half-wavelength. These ambiguities can, however, be easily resolved and the error of the final Doppler measurement should depend only on the errors in the phase measurement and the time span over which measurements are taken. For instance, if one assumes that a phase measurement can be performed to an accuracy of 10° rms at the beginning and end of a 1-sec interval, then the Earth-directed component of the BVS velocity could be estimated to 1 part in 274 (0.36%). However, it appears difficult to resolve the Doppler measurements into orthogonal Venus coordinates.

Measurement of wind velocity is possible using an onboard radar. The following data would be available from this radar: 1) altitude vs time; 2) Doppler data from both forward-looking and rearward-looking beams vs time; and 3) orthogonal Doppler data from antenna beams directed to the right and left of the BVS vs time. The altitude and Doppler data could be stored and transmitted to Earth at regular intervals to assist in determining the BVS trajectory.

Typically for a surface temperature measurement with a microwave radiometer, with an antenna half-power beamwidth of 40°, the brightness temperature measurement of the Venus surface would be averaged over approximately 50 km, and a 1° uncertainty in longitude and latitude in the position determination measurement could, therefore, give a ±100 km error in locating this area on the Venus surface.

Position Determination Systems

Position determination systems can be grouped according to the particular mission of the BVS. A Venus flyby spacecraft mission or a Venus/Mercury mission with a BVS would be limited to tracking the BVS with Earth-based equipment, while a BVS mission with an orbiter could use tracking equipment on the orbiter. As shown in Fig. 11, the use of Doppler or range measurements can accurately locate the BVS with respect to the orbiter. For example, a one-sigma error of 1 m/sec in the Doppler measurement and 5 km in the ranging measurement result in BVS position errors of less than 50 km with the station more than 10° from the orbital plane.

Table 3 lists the above system as well as those systems that do not use a companion orbiter. Possible measurements that can be obtained with onboard sensors are: nadir direction (local vertical); direction to the sun (solar zenith angle); and direction to Earth.

In addition to these measurements, Earth-based measurements of range and Doppler to the BVS should be available. In general, any two of the aforementioned measurements will define a line of position, while any three measurements will uniquely locate the BVS.

Nadir direction can be measured with a radar or an accelerometer. This appears to be within the current state

Table 3 BVS position determination systems

BVS mission	Measurement	Comments and conclusions
With orbiter	(I) Three range measurements: orbiter to BVS (II) Orbiter position and trajectory	Covariance matrix analysis (error analysis) indicates singularities in orbital plane.
	(I) Three Doppler measurements: orbiter to BVS (II) Orbiter position and trajectory	
Without orbiter utilizing onboard sensors	(I) Range to BVS (transponder) (II) Angle between local vertical and sun (III) BVS altitude	Opaqueness of clouds major problem. Need microwave radiometer sun-sensor to operate above and below clouds. Sensor accuracy requirements nominal.
	(I) Angle beween localvertical and Earth (II) Doppler: BVS to Earth (III) Relative Venus surface velocity	Earth angle measurement accuracy requires large antenna or interferometer. Precise antenna pointing or self-phased array transponder onboard BVS, accurate relative velocity measurement required.
	(I) Angle between local vertical and sun (II) Angle between local vertical and Earth (III) BVS altitude	Completely self-contained, onboard system. All direction measurements onboard, hence no ambiguities; nominal equipment requirements. Additional velocity measurements helpful.
Without orbiter utilizing Earth-based sensors	(I) Range to BVS (transponder) (II) Doppler: BVS to Earth (III) Monopulse angle	Angular resolution of phase-comparison monopulse system insufficient; useful for space tracking, orbiter trajectory and establishment of initial conditions.
	(I) Range to BVS (transponder) (II) Range to Venus subradar point (III) Interferometer angle (IV) BVS altitude	Venus subradar point uncertainty requires excessively long integration times. Not feasible with high wind velocities. High implementation cost.
	(I) Range to BVS (transponder) (II) Range & Doppler to surface transponder (III) Interferometer angle (IV) BVS altitude	Small transponder drop-probe required to establish two discrete point sources. NASA-DSN implementation problems.

of the art unless extremely violent wind gusts are encountered. The measurement of sun direction (solar zenith angle) cannot be achieved with a conventional sun sensor because of the clouds; this measurement will require a microwave radiometer operating around X-band that should be impervious to the atmosphere. The direction to Earth can also be measured readily using a direct communication link between the BVS and Earth-based receivers.

The position determination systems that use only Earth-based sensors in conjunction with a transponder onboard the BVS have the advantage of performing direct measurements from Earth; therefore, only a single error is involved in the position measurement. However, because the Venus subtended angle as viewed from Earth is only 33 sec, extremely accurate angular data must be obtained to locate the BVS within this angle using Earth-based sensors.

With the DSN measuring the station transponder range, its Doppler shift, and solar zenith angle, it has been estimated that this combination of data can locate the BVS to within $\pm 1°$ longitude and latitude. This same transponder can be tracked, it is estimated, to within 20 cm/sec of its Earth-directed velocity from Doppler measurement. However, if the station drifts across the terminator the solar zenith angle is lost. A method that may not be dependent on the solar zenith angle uses recursive filtering theory. This method applies all of the engineering and science measurements that can be statistically modeled to define an observation vector. Actual and predicted values of this observation vector are then compared to estimate a state vector whose elements include the position of the BVS. Further studies should be undertaken before a recommended system is selected for a particular mission.

Conclusion

Venus missions involving atmospheric entry and long-term flotation can be accomplished in the mid-1970's if a modest development program continues in the areas of heat shield, superpressure balloon, and BVS tracking. The achievement of an understanding of ablative material response through testing and analysis, as well as developing a better understanding of the subject of radiative heating prediction, represent technology developments that form the basis for achieving a reliable heat protection system for any Venus mission.

Further balloon materials investigation, both analysis and testing, as well as development in design and fabrication techniques for superpressure balloons culminating in complete system testing will produce a rugged, highly reliable balloon for the Venus missions. Studies should be continued to derive the most suitable tracking concept and to implement this system.

References

[1] Baxter, J. F. et al., "Final Report, Buoyant Venus Station Mission Feasibility Study for 1972–1973 Launch Opportunities," NASA CR-66725-1 (Vol. I), Jan. 1969, Martin Marietta Corp., Denver, Colo.

[2] Sadin, S. R. and Frank, R. E., "Buoyant Station for the 70's," AAS Symposium, July 15–16, 1968.

[3] Barger, A. R., "Atmosphere of Venus: A Review of Recent Observations and Theories," AAS Symposium, July 15–16, 1968.

[4] Ohring, G. W., Tang, W., and Mariano, J., "Planetary Meteorology," NASA CR-280, 1965, GCA Corp., Bedford, Mass.

[5] Spiegel, J. M., Wolf, F., and Zeh, D. W., "Simulation of Venus Atmospheric Entry by Earth Reentry," AIAA Paper 68-1148, Williamsburg, Va., 1968.

[6] Arnett, J. C. and Carroll, P. C., "Materials Feasibility Tests," PR-22-69-17, June 1969, Martin Marietta Corp., Denver, Colo.

[7] Koppl, W., "Position Determination of BVS Spacecraft, Summary Report," TN 1610-69-23, April 1969, Martin Marietta Corp., Denver, Colo.