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PIONEER VENUS

Report of a Study by the

Science Steering Group – June 1972

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035

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PREFACE

To date, the U.S. planetary exploration program has included two fly-by spacecraft that have made observations of Venus: Mariner 2 (1962) and Mariner 5 (1967). The Mariner Venus/Mercury 1973 fly-by is the only currently approved mission to continue exploration of this mysterious, cloud-covered planet. For several years, the scientific community has advocated continued exploration of Venus using a series of low-cost probe and orbiter missions launched at successive opportunities. Detailed studies of this Planetary Explorer/Pioneer-Venus Concept have proceeded to the point where NASA is now planning an FY'74 program start which will permit a multiple-probe mission to be launched in the 1976/1977 launch window and an orbiter mission to be launched at the 1978 opportunity. In concert with these plans, NASA selected a Pioneer-Venus Science Steering Group (SSG) in January 1972.

The SSG, meeting with Pioneer-Venus Project personnel over the period February through June 1972, developed in great detail the scientific rationale and objectives of these early missions. Candidate payloads and spacecraft targeting strategies were also developed based on current knowledge of spacecraft configurations, capabilities and constraints. Although these latter factors will no doubt be altered somewhat during the Phase B design studies to be conducted during the period October 1972 through July 1973, the candidate payloads and measurement criteria developed should be a useful guide both for the Payload Selection Committee which will select experiments and experimenters during the latter part of this year for the multiple-probe mission and for the Phase B contractors.

This document is the final report of the SSG and contains a summary of the findings of the Group. Chapter 1 retraces the history of the Pioneer-Venus program and outlines the basic issues and background information required to understand the rationale behind the SSG recommendations. Chapter 2 contains a detailed exposition of the 1976/1977 multiple-probe mission and Chapter 3 contains in somewhat less detail the findings associated with the 1978 orbiter mission and a brief discussion of a follow-on 1980 mission. The appendices contain detailed technical data intended to amplify some of the major recommendations contained within the text.

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Chapter 1

INTRODUCTION

EARLY HISTORY

The history of Pioneer-Venus began in 1967 when a consortium of scientists was formed to explore the feasibility of a simple entry probe for the study of the Venus atmosphere. A study contract with the AVCO Corporation was sponsored by Goddard Space Flight Center (GSFC) with the science consortium advising on the goals, objectives, and possible instrumentation for such entry probes.

In 1968 an in-house study was initiated at GSFC to study the feasibility of small planetary orbiters using Explorer (IMP) technology and the Delta launch vehicle. The spacecraft was called the Planetary Explorer in this study.

GSFC issued the Planetary Explorer Phase A Technical Plan in October 1969. This report endorsed the feasibility of Delta-launched, spin-stabilized orbiters for missions to the terrestrial planets. During the same year, GSFC sponsored a contract study with AVCO Corporation for a Delta Class Venus Probe mission. At the end of 1969, NASA Headquarters recommended the merger of the Delta Class Venus Probe and the Planetary Explorer orbiter. This led to the concept of a Universal Bus; i.e., a spacecraft design that could be used either to deliver multiple entry probes into the atmosphere of Venus or to orbit the planet. The study by AVCO and the in-house effort at GSFC established the feasibility of the Planetary Explorer concept, as shown in the GSFC Phase A Report and Universal Bus Description (May 1971). In accord with recommendations of the NAS Venus Study and the NAS Priorities Study (1970), the Planetary Explorer Mission sequence included a dual multiple-probe mission followed by an orbiter and then a second entry-probe mission. For programmatic reasons, the originally conceived multiple-probe mission for the 1975 launch opportunity had to be deferred to the 1976/77 launch opportunity.

CURRENT STATUS

In 1971 the Planetary Explorer Study was terminated at GSFC and reinstituted as Pioneer-Venus at Ames Research Center (ARC). The Pioneer-Venus Study team was organized at ARC in January 1972 with the tasks of initiating the Phase B effort, the System Definition Phase, and assisting the Science Steering Group in the definition of the scientific instrument payload.

The Pioneer-Venus Science Steering Group was established by NASA to enlist wide-spread participation of the scientific community in the early selection of the science requirements for the Pioneer-Venus missions. The opportunity to propose for participation in the planning effort was announced 1 July 1971. Proposals were evaluated by customary NASA procedures and the Science Steering Group was formed in early January 1972.

The tasks assigned to the Science Steering Group were: (1) Definition of a typical payload for the first probe mission (1976-77); (2) Recommendation of strategy and objectives for the orbiter and/or probe missions for the 1978 and 1980 opportunities; and (3) Identification of long lead time and critical experiment development items, and the necessary supporting research.

Following the SSG activities will be the issuance of the Announcement of Flight Opportunities (AFO) in August 1972. The science payload for the initial dual-probe mission, January 1977, will be selected by January 1973. Some long-lead time development has already been initiated.

All of these activities are preliminary to preparation for the proposed program start in January 1974. Approval of the project at that time will signal the Execution Phase which will culminate with the dual, multiple-probe flight missions in January 1977, the orbiter flight mission in August 1978, and the follow-on flight mission in 1980. Project Management was established at Ames Research Center as an extension of the present Pioneer Program. A contract will be awarded to one of the study teams for spacecraft design and development.

The Delta 2914 launch vehicle will be used with tracking and data acquisition support provided by the 26-meter and 64-meter antenna systems of the Deep Space Network (DSN). Mission control and off-line data record preparation will be performed in those facilities established to support the Pioneer 6, 7, 8, 9, 10, and G flight missions.

International cooperation has been suggested for the Pioneer-Venus mission series. Initial planning has therefore begun to determine the feasibility of cooperating with ESRO for the orbiter mission, but specific agreements have not been made at this time.

1970 NAS VENUS STUDY

The Pioneer-Venus Science Steering Group based its work on the NAS Venus Study (June 1970). This study developed a scientific program for the magnetosphere, the upper and lower atmosphere, and the solid surface of Venus. The study proposed a continuing program using relatively low cost spinning spacecraft launched on Delta rockets.

In the course of the SSG deliberations, the science rationale in the NAS Venus Study report has been re-examined in detail; we found it unnecessary to make any significant modifications. Although our knowledge of Venus has advanced in the past two years, the major research areas identified in the report will remain vital and important for a long time to come. The Soviet successes in this field and their relationship to the NAS Venus Study are considered in the next section of this report.

The approach of the NAS Venus Study emphasizes the essential complexity of planetary phenomena; no phenomenon can be understood by itself. Measurements of many related quantities must be made simultaneously at different altitudes, and often at widely differing locations. In circumstances of such complexity, a continuing program involving probes and orbiters is an extremely powerful approach. To illustrate this proposition, we have analyzed the probable success of probes and orbiters in terms of 24 "First Order" Science Questions. It must be emphasized that the separation into first-order questions is arbitrary and is done solely to provide a basis for comparison between ground level measurements, Mariners 2 and 5, the whole Venera series, Pioneer-Venus probes and orbiters, and the Venus/Mercury fly-by. Pioneer-Venus is not a transport system for the sake of independent investigations. It is intended to address itself to a few grand questions about the planet. The selected experiments will support and complement each other to this end. Details of the analysis are given in Appendix 1, where it is shown that the anticipated increases in knowledge from Pioneer-Venus probes and orbiters greatly exceed those achieved or expected from other sources.

The NAS Venus Study directly addresses the question: "why explore Venus now?" It points to the great advances in planetary science in recent years and our increasing understanding of fundamental problems such as the origin of life and the origin of the solar system. Because of the ubiquitous clouds, we know almost nothing about Venus below the cloud tops. If our knowledge of the solar system is to advance evenly, we require a more intense research effort on this planet. In addition, the results of this research can add to our knowledge of Earth. The relatively advanced nature of theoretical work means that a rapid advance in knowledge should be possible with a limited number of direct measurements.

We strongly endorse these views, which are at least as true in 1972 as they were in 1970. We should explore Venus now because of its novelty, its importance to more than one branch of science, and because it is feasible within the framework of a relatively economical program.

SOVIET, U.S., AND ESRO PROGRAMS

The Soviet contribution to the scientific exploration of Venus is summarized in Table 1. These data were compiled from a recent document published by the Library of Congress, "Soviet Space Programs, 1966-70, Staff Report, Senate Document No. 92-51." The Venera series includes only those spacecraft that escaped from the Earth's gravitational field and achieved a Venus trajectory.

On 27 March 1972, the Russians launched Venera 8, weighing 1180 kg, the same as Venera 7. It is believed to be carrying experiments to measure atmospheric temperature and pressure and to analyze the Venusian soil, apparently with an X-ray fluorescence device.

Subsequent to the flight of Venera 7, the Space Science Board asked a panel under the chairmanship of Professor Thomas M. Donahue of the University of Pittsburgh to reassess the recommendations of the NAS Venus Study in light of the successful landing of Venera 7.

Table 1. Soviet Venus Flights

Launch Date	Name	Weight (kg.)	Results
12 Feb. 1961	Venera 1	644	Communications failed at 7,600,000 km from Earth, Feb. 27. Passed Venus at 100,000 km, May 19, 1961.
12 Nov. 1965	Venera 2	963	Communications failed before arrival. Passed Venus at 24,000 km on Feb. 27, 1966.
16 Nov. 1965	Venera 3	960	Communications failed before arrival. Struck Venus 450 km from center of visible disk, Mar. 1, 1966.
12 June 1967	Venera 4	1106	Measurements of Venus returned both from bus and from atmospheric probe probably within 25 km of the surface. Provided the most detailed profile yet of atmospheric composition, pressure, and temperature. Bus burned in atmosphere. Capsule had parachute.
5 Jan. 1969	Venera 5	1130	Measurements of Venus returned both from bus and from atmospheric probe which refined the data of the previous flight but which also ceased signals before reaching the surface.
10 Jan. 1969	Venera 6	1130	Measurements of Venus returned both from bus and from atmospheric probe which refined the data of Venera 4, but which also ceased signals before reaching the surface.
17 Aug. 1970	Venera 7	1180	Measurements of Venus returned from bus and atmospheric probe strengthened to achieve the continuing mission. Was success in landing, returning 23 min. of data from the surface.

To quote from that report:

> "...The panel has been asked to address itself to two specific questions:
>
> 1. "Do the results obtained by Venera 7 in any way alter the program of study recommended in the 1970 Space Science Board report?

2. "Has this Soviet success demonstrated a capacity and a will for Venus exploration in the Soviet space program strong enough to warrant leaving Venus to the Russians while the United States more intensively develops other space programs?

"Our answers to both questions are "no". The Planetary Explorer program recommended in the Venus study would be a well-articulated, intensive study of the planet designed to attempt to answer a list of first-order questions. Among these are the number, thickness, and composition of the cloud layers; the nature of the circulation; explanation of the high surface temperature; the reason for the lack of water and the remarkable stability of the CO_2 atmosphere; the nature of the interaction of the solar wind with the planet; the elemental composition of the surface; the distribution of mass and magnetic field strength; and the measurement of seismic activity. Venera 7 was a highly specialized probe designed to perform only two functions -- to measure atmospheric temperature and pressure down to the surface of Venus. It succeeded in obtaining the temperature and confirmed the most widely held expectation -- that the surface temperature is high. It has in no way changed the conditions on which the Venus study was based or answered any of the questions that Planetary Explorers are designed to answer. We can find no reason, therefore, to recommend changes in the scientific objectives set forth in previous Board studies...

"We therefore urge that NASA follow the recommendations of the 1970 Space Science Board Study as contained in the report entitled, Venus: Strategy for Exploration."

After an independent study of the Soviet Venus Program, the SSG agrees with this assessment of the Venera Program.

The past eleven years of Soviet exploration of Venus have produced "in situ" measurements of the lower atmosphere such as pressure, temperature, density, and gross atmospheric composition. This information, along with that from other sources, has been extremely valuable and allows for the optimization of our payloads to meet the scientific objectives of the program.

The NAS Venus Study exposes a wide range of scientific problems on Venus concerned with the magnetosphere, the upper atmosphere, the lower atmosphere, and the solid planet. As with most areas of geophysics, new knowledge will lead to new questions, new theories, and a need for further measurements. We anticipate that, in the broad context of the physics and dynamics of the solar system, interest in Venus will continue for many decades and will need resources from the United States, the Soviet and European space programs. It is not our practice in other fields of scientific endeavor to divide the field into areas of exclusive national interest, and there is no reason to consider this course in an area so rich in problems as Venus, particularly when the United States capability in sophisticated instrumentation can make such effective contributions. We see the opportunity for a real scientific collaboration in which United States, Soviet Union, and ESRO programs can build upon and complement each other within the agreements for collaboration that have been negotiated between governments and national space programs. We are confident that the Pioneer-Venus program will place the United States in the forefront of such an international collaboration.

THE LOW-COST PIONEER-VENUS CONCEPT

In 1968 the NAS study Planetary Exploration: 1968-1975 recommended that a need existed for modest, relatively low-cost missions to the planets. The first priority recommended by this study was: "a program of Pioneer/IMP class spinning spacecraft for orbiting Venus and Mars at each opportunity and for exploratory missions to other targets." Since then, the concept of Delta-launched entry probes and orbiters has become established in a universal bus concept.

The present report addresses itself to a three-mission set. In the context of the NAS Venus Study recommendations, however, these must be viewed as part of a continuing series of missions to Venus, preferably at each opportunity.

The advantages of a low-cost series lie in: (1) an orderly progression from simple early experiments to more elaborate later experiments; (2) active participation of many scientists from different disciplines by increasing the opportunity for exploration; and (3) the flexibility whereby under fiscal constraints the program can be reduced in frequency without complete cutoff and loss of experimenters.

As far as entry probe missions are concerned, the low-cost Pioneer-Venus class offers all of the payload capability needed to answer the first-order questions on the atmosphere of Venus. For orbiter and balloon type missions, the Pioneer-Venus class spacecraft affords the opportunity to make major contributions to our understanding of Venus. Larger spacecraft have been considered for Venus exploration; however, their increased capability is significantly offset by the increased costs and the loss of the positive advantages of a low-cost series, at least at the present stage of Venus exploration. As more elaborate questions are asked, larger and more complex spacecraft may be required, but the SSG strongly endorses the position of the NAS Venus Study on the desirability of the low-cost Pioneer approach for the initial stages of Venus exploration.

Besides using a spacecraft whose capability is not excessive for the missions, this low-cost approach includes the use of developed technology, the simplest experimental concepts, judicious testing and quality control, and avoidance of complex subsystems which tend to be expensive if they are to be reliable. The Pioneer-Venus concept is therefore well suited to strict cost-control.

COST CONTROL

(The following statement reflects the policy of the Planetary Programs Division of the Office of Space Sciences and is fully endorsed by the Pioneer-Venus Science Steering Group.)

The NAS Venus Study clearly recognized that the science value of its program is strongly coupled to the cost of implementation. There are many demands placed on the limited resources available for space science. The priority of one mission, therefore, with respect to any other, is heavily dependent upon the resources required to effect that mission, as well as to its intrinsic science value. NASA's detailed cost estimate of the Pioneer-Venus Program, consisting of the dual probe mission in the 1976/77 opportunity, the orbiter in the 1978 opportunity, and a follow-on mission in the 1980 opportunity, indicates that an absolute cost ceiling of $200,000,000* in terms of Fiscal Year 1972 dollars should be imposed on this program. This ceiling is in consonance with the position taken by the NAS. It is the intent of NASA to manage the program so that this cost ceiling will not be violated. The achievement of this cost objective will demand cooperation and discipline by all of the participants. The scientists involved in the program must play a vital role in achieving the mission objectives within the cost constraints.

The program cost presented to the Space Science Board in 1970, by the NAS Venus Study Group was $130,000,000. At that point, the program and the mission were fairly well defined but, as stated in the Study report, "it must be borne in mind that these figures are preliminary and reflect planning estimates rather than contractual obligations". Moreover, this cost estimate assumed that the bus would be fabricated in-house at one of the NASA Centers and hence the development cost was not reflected in this total program cost. NASA's present plan is to contract the development of the entire program to industry. The cost increment as a result of this factor is estimated to be $25,000,000. In the past year, NASA has altered the mode of charging for tracking and data acquisition. A portion of the tracking and data acquisition costs are now factored against each of the flight programs as opposed to the previous mode, where NASA's Office of Tracking and Data Acquisition assumed the total cost of mission operations as a support function. The cost increment due to this factor is $7,000,000. The apparent program cost, with these two factors included, is therefore $162,000,000 as opposed to the original estimate of $130,000,000. It must be stressed however, that this is not a program cost escalation, rather, it is a bookkeeping shift where certain cost elements are now charged directly against the flight project rather than as support functions in other elements of the NASA budget. Since 1970, an inflation factor of 5.9% per year has been experienced. Incorporating the effect of two years' increase, the estimated program cost in Fiscal Year 1972 Dollars is therefore $182,000,000. This estimate is close to recent detailed cost analysis based on the current definition of the program. An expenditure ceiling of $200,000,000 in FY 1972 dollars is therefore fully consistent with the wishes of the 1970 SSB Priorities Study for fiscal constraint in this program.

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* From a cost analysis standpoint, a probe mission has been assumed for the 1980 Venus opportunity. Launch vehicles are not included in this estimate.

It is now pertinent to consider the steps which must be taken to achieve cost control during the Execution Phase of the program. NASA is instituting a competitive Systems Design Study to achieve a detailed functional definition of each subsystem element in the spacecraft bus and the probes. It is NASA's hope that the definition will be at the level of detail where a price for procurement might be fixed for the Execution Phase of the program. For this procurement mode to be seriously considered, an equivalent level of detail in the definition of each probe or spacecraft science instrument is necessary.

This implies that the only experiments which can be considered for selection are those which have been functionally proven by either laboratory testing or flight experience. Furthermore, during the development of the science instruments, the interface between the spacecraft or the entry probes and the scientific instrument cannot be altered. It is NASA's intent to establish a firm science procurement price in the manner used for procurement of the spacecraft system. These objectives can be realistically realized in the following manner. The physical and functional interfaces between the probes and/or spacecraft and the experiment will be negotiated between NASA and the Principal Investigator. The experiment design must be established to the level required to rigidly specify a weight constraint, and a volume and form factor constraint. Furthermore, the experiment functional requirements must be established to accurately specify the power requirements for the experiment and to understand completely the interface between the experiment and the data subsystem. An Experiment Integration Guidelines Document will be developed jointly and cosigned by the experimenter and by NASA. The Principal Investigator must agree to develop his instrument within the physical and functional constraints and he must further agree to accept the schedule terms and a negotiated cost for each experiment. It will then be NASA's position that no further funding will be available to alter the spacecraft and experiment interface or the probe and experiment interface or to provide additional funding for a given experiment. The posture which must be taken by NASA in implementing the cost guidelines defined by the Space Science Board is that, if there is a conflict between incorporating a given experiment and exceeding the imposed program cost ceiling, then that experiment will be reduced in capability. A substantial proportion of the instruments have capabilities considerably in excess of requirements.

INSTRUMENT FEASIBILITY

The SSG adopted a conservative approach to the instrument complement, partly to avoid cost escalation in this area and partly because we found that new developments were not required to achieve the mission objectives. The following criteria were applied:

(1) An instrument should be known to have performed successfully in the Earth's atmosphere; no novel measurement concepts were adopted.

(2) Wherever possible, instruments should have been qualified for space or aircraft environment.

(3) If the instrument, or components of the instrument, have not been tested in a space environment, it is essential that they be so simple and rugged that their satisfactory performance can readily be proven in the laboratory.

PROPOSED MISSIONS SEQUENCE

The report of the 1970 NAS Venus Study presented a detailed scientific rationale for a four mission series of launches to Venus at consecutive opportunities beginning in 1975: Multiple probe (1975), Orbiter (1976), Lander (1978), Balloon (1980). The current SSG has carefully reviewed this scientific rationale in light of subsequent developments since June 1970 (program delay negating use of the 1975 launch opportunity, scientific findings of the Venera 7 probe in December 1970, continued analysis of earlier spacecraft data (Venera 4, 5, 6, Mariner 5), recent Earth-based observations, new theoretical developments, anticipated results from recently launched Venera 8 and Mariner Venus/Mercury 1973). We make the following recommendations.

(1) NASA should proceed with detailed planning for the following mission set: Multiple probe (1976/1977) and Single Orbiter (1978). Specific recommendations and candidate payloads for these missions are discussed in Chapters 2 and 3. The SSG gave considerably more emphasis to the multiple probe mission. This ordering of the missions is made for the following reasons:

- Most of the key scientific questions concerning Venus require "in situ" atmospheric measurements below the cloud tops extending down close to the surface. Since the required technology and scientific instruments are within the state-of-the-art, a probe mission at the first opportunity is therefore desirable.
- A dual-launch capability is recommended for the obvious advantages of redundancy and for the ability to retarget the second launch, assuming first-launch success, to probe extensive regions of the planet.
- Since many of the first-order questions concerning Venus cannot be addressed in the first mission, it appears highly desirable that the third mission (1980) also be a probe mission. Since launch opportunities occur every 19 months and efficient mission planning dictates longer lead times than this, a probe mission in 1976 is required to allow the results of that mission to be incorporated in the 1980 mission planning.
- Although a dual orbiter mission has certain attractive features, the SSG does not feel that the additional costs involved justify more than a single orbiter in 1978.

(2) In consonance with the 1970 NAS Venus Study, the SSG recommends that NASA initiate plans for a 1980 probe-type mission. Detailed planning should await the scientific findings of the 1976 multiple probe results. In anticipation of these results, and perhaps more importantly in recognition of the scientific questions which will not be addressed by the first two missions, NASA should explore the technological and economic impact to the program of a long-lived lander for this mission.

(3) The SSG strongly endorses the concept of scientific investigation of Venus at each launch opportunity following the above recommended three-mission set. However, it is not possible, nor desirable, to attempt to detail any follow-on missions at this time.

Chapter 2

1976/77 MULTIPLE PROBE MISSION

MISSION DESCRIPTION AND SPACECRAFT CONSTRAINTS

The mission description presented here is an update of the GSFC Phase "A" study. It is subject to change, as a result of the Phase "B" study, which will begin in October 1972. Nevertheless, it represents the most recent description of the 1976/77 Venus mission.

The mission will consist of two identical spacecraft and payloads launched during the December 1976 through January 1977 launch window. Each spacecraft will consist of a bus, a large probe, and three small probes. The spacecraft will be spin stabilized and will use solar power. It will weigh about 840 pounds when launched by a Delta 2914 launch vehicle.

Cruise from Earth to Venus will last about 125 days and will include two or three midcourse maneuvers to control the trajectory. During the cruise phase of the mission, the telemetry bit rate will be about 16 bits per second.

The probes will be separated from the bus about 10 to 20 days before entry. Before separation, the probes will be turned on for a checkout period and their state of health will be telemetered to Earth. After separation, the probes will be inactive to save battery power until they are turned on by a timer just before entry. From separation until the end of the mission, all probe events will be programmed by an on-board sequencer.

The two large probes will include an aeroshell and heat shield, a parachute system to reduce descent rate, and a pressure vessel to protect the experiments. The aeroshell and heat shield will protect the pressure vessel during entry and provide subsonic flight at an altitude of about 70 km. The maximum entry deceleration will be about 300 g's. The parachute system will be deployed at about 70 km to separate the heat shield and provide a slow descent through the atmosphere. The pressure vessel will contain all probe experiments and electronics. Its inside shape will be approximately that of a 22-inch diameter sphere. It will contain heated windows to provide a view for optical experiments.

After passing through the upper atmosphere, the parachute will be separated, and the pressure vessel will fall free to the surface. The mission is designed to end when the pressure vessel reaches the surface, about 1.5 hours after entry. Data will be collected and stored during entry. After entry, stored and real-time data will be transmitted directly to Earth. The bit rate will be about 100 bits per second. The large probes must be targeted within 40° to 50° of the sub-earth point to ensure that the Earth remains within their antenna beam.

The six small probes will be identical. They will include an integrated structure containing the aeroshell, heat shield, and pressure vessel. The integrated structure will protect the experiments until surface impact. The inside shape of the pressure vessel will be approximately that of an 11-inch diameter sphere. The maximum entry deceleration will be about 500 g's. The small probes will fall free to the surface. Their mission is designed to end about one hour after entry. Some data may be stored during entry. After entry, stored and real-time data will be transmitted directly to Earth. The bit rate will be about 4 bits per second. The small probes must be targeted within about 70° of the sub-earth point to prevent excessive signal attenuation by the atmosphere.

The two busses will be designed to enter the Venus atmosphere at a shallow entry angle and transmit data to Earth until they burn up. The bus bit rate during entry will be about 300 bits per second.

LARGE PROBE

Scientific Objectives

The objective of the large probe is a sounding through the whole atmosphere, with measurements of the structure, composition, and clouds. It also contributes to the mission of the small probes, by making a fourth set of measurements and by providing data needed to interpret their measurements. However, the primary emphasis is on the energy balance and clouds -- their nature, distribution, composition, and interaction with light and with thermal radiation. The measurements are expected to define the present state of the atmosphere and the planetary heat balance. An important further result will be information on the origin and evolution of the planets. Because of the high surface temperature, a close approach to thermodynamic and chemical equilibrium with the atmosphere is expected and many unfamiliar elements and compounds become volatile. These are the substances that give the best clues to conditions in the solar nebula at the time of accretion.

No attempt is to be made, in this first mission, to collect and analyze the cloud particles. This very difficult class of experiment is unnecessary for the most probable type of cloud, a condensate. The vapor of such a material must be present in and below the cloud, and the mass-spectrometer experiment is carefully designed to measure such vapors. Optical instruments will give the presence and distribution of particles; thus, with a knowledge of temperature and the vapors present, a model of the cloud can be constructed. If dust (non-condensing material) is a major component of the planet-wide blanket, it must be present all the way to the surface. The optical instruments will observe this situation, but no direct measurement of composition will be possible. Because condensates are more likely, we consider it appropriate to defer any attempt at dust analysis to a later mission, contingent on a discovery of dust by the first soundings. Geochemically-based speculation has suggested mercury halides, and mercury itself. The topmost clouds, visible from Earth, have been interpreted as ice, iron chloride, or dirty hydrochloric acid. Another important question is the effect of latent heat of condensation on the dynamics of the atmosphere.

In fact, the whole planetary heat budget is bound up with the clouds. The high surface temperature of Venus has been explained, on the one hand, by a greenhouse model, which requires that solar energy penetrate deeply into the atmosphere. On the other hand, dynamical theories have been proposed which operate even if the solar energy is deposited mainly in the upper cloud layers. It will be necessary to determine the penetration of solar radiation into the atmosphere, as well as the effective level of thermal infrared loss, to resolve these divergent views. If individual cloud layers are present, their location, number, and radiative properties must be known. In addition, any possible information should be gathered on their horizontal structure.

Measurements of pressure, temperature, and acceleration are routine in the Earth's atmosphere. The accelerometers give the density and temperature in the entry region, and give information on winds and turbulence at lower altitudes. The primary instrument for composition measurement is a mass spectrometer, with a special inlet system to allow sampling at high pressures and temperatures. Its measurements fall into three general classes: (1) composition of major gases such as CO_2, and possibly N_2 or Ar; (2) composition of vapors that may form the various cloud layers; and (3) other trace gases, primarily the inert ones. Backup methods may be desirable for certain gases; radiation from the shock layer during entry can be observed by simple photometers; and a hygrometer can be included if proved to be specific to water vapor in the presence of acid vapors.

Cloud particles can be observed in various ways. Vertical distributions should be measured from several probes penetrating the atmosphere at diverse locations. Some of the small probes will enter a dark part of the planet during the 1976/77 missions; this renders it necessary to place nephelometers on these probes. These nephelometers need only register the presence of clouds or hazes. A more sophisticated nephelometer should be placed on the main probe as a backup to the other instruments.

Measurements of cloud-particle size are required over a 1 to 500 μ range. The instrument should be capable of making single-particle-size measurements at high concentrations (10^3 to 10^4 cm^{-3}) and be relatively insensitive to particle orientation, shape, or refractive index, because particle morphology is unknown. These constraints make particle-size detection by imaging or extinction techniques more suitable than by scattering in the backward direction.

Because the parachute on the main probe will be deployed at or below 70 km, cloud particles above this altitude cannot be measured with an "in situ" particle-size spectrometer. Astronomical inferences about the upper layers of the Venus atmosphere depend on assumptions regarding the optical characteristics of the upper clouds. Information can, in principle, be obtained from measurements of the aureole.

To obtain the radiative heat budget, it is desirable to measure directly where the incident solar energy is deposited. The best measurement is of net flux, the difference between downward and upward fluxes. Measurements of infrared (planetary) radiation could also be made. They could be broadband or, if necessary, restricted to a few wavelength regions.

Candidate Payload

The instrument payload for the large probe is listed in Table 2. The last three instruments are of lower priority because their measurements are redundant to other primary experiments. However, all instruments are desirable, and the complete list does not appear to be a heavy burden on the mission.

Table 2. Large Probe Payload

Instrument or Measurement	Weight (lb)	Power (Watts)	Priority Category
Temperature	1.5	0.2	A
Pressure	2.0	0.8	A
Accelerometers and Miniseismometer	2.5	3	A
Transponder	3	4	A
Mass Spectrometer	20	12	A
Cloud Particle Size Analyzer	8	20	A
Aureole and Extinction	4	1	A
Solar Flux	4	4	A
Infrared Flux	5	2.5	A
Hygrometer	1	0.2	B
Nephelometer	2.5	2	B
Shock-Layer Radiometer	2	1	C
TOTAL	55.5	50.7	

Individual Instruments

Temperature and Pressure

A principal objective of the multiple probe mission is to obtain, with high accuracy, the temperature-pressure structure of the lower atmosphere at widely separated points over the planet to define the gradients which drive the planetary circulation. Because it is their differences which are important, the measurements at the widely separated points must be made with high relative accuracy. (See Appendix 2.) We have examined the tested, available techniques for such measurements and conclude that they can be achieved to the necessary accuracy.

The measurements should take, as a point of departure, the similar measurements routinely made in the Earth's atmosphere with radiosondes and on aircraft, and which were made in the PAET entry probe atmosphere structure experiment. Either platinum resistance thermometers or fine wire thermocouples are possible choices. Radiative shielding may be desirable. The sensor should be mounted outside the vehicle boundary layer, where it will experience no convective exchange with the probe itself. There are no fundamental problems in measuring the atmospheric temperature to the accuracy goals stated in Appendix 2.

Pressure sensing with existing techniques will not be a problem. There are numerous, commercially available transducers with the following characteristics: rated pressures, 110 bars or greater; repeatability, 0.25%; temperature sensitivity, 0.036%/°C; acceleration sensitivity, less than 5×10^{-5} full scale reading per g. In some cases, they have been flight qualified. Some of these sensors are miniaturized; e.g., 3 mm diameter by 5 mm long, including electronics. The installation of the sensors on the probes will require close attention. For example, the sensor should be thermally isolated from the external environment. This demands an internal, well-insulated location of the sensor and also suggests that gases be admitted through a tube of sufficient heat capacity to absorb the heat carried by the small quantity of gas admitted. The sensor temperature must also be monitored and telemetered occasionally, to an accuracy of 3°C or better. Provision should be made for calibration of any zero shifts in space, prior to entry.

Acceleration

Measurements of the probe accelerations during various mission phases will bear on several scientific objectives:

(1) Deceleration history during entry and descent will provide information on the temperature structure of the atmosphere.

(2) Decelerations measured in the atmosphere can be analyzed to define winds and turbulence.

(3) For one mode of data analysis, the mean molecular weight of the atmospheric gases can be obtained from measured accelerations, pressures, and temperatures.

(4) The accelerations will be used to define the trajectory followed by the probe, and in this way, will interact with and complement the doubly differenced, very long baseline interferometry (DLBI) determination of the entry trajectory and winds. (See Appendix 3.)

(5) If the probe should survive landing, an available circuit board added to the sensor electronics will permit the detection and evaluation of the noise background for seismometry, at the level of 1/10 milligal or less. (As noted in the NAS Venus Study, this information will help in the planning of possible future seismic measurements.)

(6) The landed accelerometer, if it survives, will give the surface gravity and thus the radial distance from the planetary center with an accuracy of 0.4 km.

The accelerometer responds to the ambient atmospheric density and velocity through the known aerodynamics of the probe. The physics is particularly simple during the supersonic part of entry; density and pressure profiles, accurate to a few percent, can be obtained at heights where direct measurements are impossible. During the low-velocity part of the mission, the response is primarily to turbulence, a quantity of major significance to atmospheric dynamics. Integration of the outputs permits an "inertial navigation" by which the final position of the probe can be obtained within a few km. An average data rate of 3 bits/second should permit all objectives to be realized.

Transponder

Closed-loop tracking is an important technique giving an accurate knowledge of radial distance and velocity. (See Appendix 3.) In conjunction with DLBI tracking in the orthogonal direction, the result will be a complete three-dimensional picture of the probe's motion, from which mean winds and turbulence can again be inferred.

Mass Spectrometer

The mass spectrometer system will operate deep in the atmosphere and thus at the highest pressure and temperature anticipated near the planet's surface. It has three fundamental objectives: (1) to identify chemically reactive constituents of the atmosphere; (2) to identify inert gases; and (3) to provide abundance ratios of certain constituents. (See Appendix 4.)

Laboratory tests with representative instruments demonstrate that these requirements are within the state-of-the-art. A crucial aspect, reducing a high pressure sample (100 bar) to the low pressure required for analysis by a spectrometer (10^{-8} bar), has been repeatedly accomplished at temperatures as high as 1000°C, well above the Venus surface atmosphere temperature. In addition to N_2, He, O_2, and CO_2, representative reactants such as HNO_3, HCl, HgI_2, H_2SO_4, $HgBr_2$, H_2O have been employed in the studies demonstrating that the anticipated environment of Venus is amenable to mass spectrometric exploration.

Reduction of the pressure to the required levels requires passage of the sample through devices of extremely low conductance, posing questions of blockage, sample-surface reactions, mass discrimination, etc. Experience shows that these phenomena are real, but are not detrimental to achieving acceptable measurement goals. There are areas where improvements over existing capability can be expected, primarily in relation to quantitative analysis. For example, specific modification of a sample (chemical cleaning) would improve inert-gas detection and analysis. Such manipulation is routinely accomplished in commercial and laboratory analysis.

The SSG feels that a quantitative analysis of the Venus atmosphere is highly desirable and therefore recommends intensive development of several alternative approaches to sampling techniques for the mass spectrometer experiment.

The question of cloud-particle composition is discussed on Page 11. Any condensables are to be detected as vapors; if dust particles are present, they will be measured only by optical instruments. Collection and vaporization of dust particles would be a formidable task. It should not be attempted until the need has been demonstrated.

Shock-layer Radiometer

During the high speed phase of the entry, a strong bow shock wave precedes the blunt probe. It stands away from the probe face by a small distance on the order of 1 cm, depending on probe size and geometry. This thin layer is luminescent, for a short time at high speeds, because its temperature may range up to 11,000°K. Spectral features in radiation from the layer are determined by the atmospheric composition, and conversely, composition can be derived from the spectrum. Radiometer channels are selected to measure particular features. For atmospheres containing N_2 and CO_2, CN violet radiation is by far the most prominent feature. It is a measure of the CN formed at equilibrium in the shock layer, from which the N_2 and CO_2 fractions are calculable. Nitrogen is also signaled by the presence of N_2^+ molecular bands. Hydrogen (from water) gives rise to OH bands at 3400 A and to CH and NH features as well. Noble gases are detectable from their effect on shock layer temperature. The radiometer has been demonstrated on the PAET entry probe, where it gave the composition of the Earth's atmosphere with excellent accuracy. It is a useful backup device for measurement of the bulk species (as opposed to trace species) in the Venus atmosphere. However, it must be given lower priority than the mass spectrometer, which can address itself to more species and to trace quantities.

Hygrometer

The water-vapor content of the Venus atmosphere is particularly important to studies of planetary origin, microwave and optical absorption, and formation of clouds. We feel that this importance justifies a small dedicated sensor (a hygrometer) in addition to the mass spectrometer.

Any device that works by electrolytic conductivity is ruled out by the known presence of HCl, a strong electrolyte. Preliminary examination suggests that one available device, at least, may be immune to such difficulties. If this indication is borne out by further tests, we believe that a hygrometer is worth serious consideration. An upper limit to the amount of water in the Venus atmosphere has already been established; therefore, there is no reason for the instrument to measure or indeed survive at temperatures above about 100°C. In the hot, low regions of the atmosphere it is expected that the H_2O mixing ratio will be independent of height.

Particle-Size Spectrometer

This recently-developed instrument avoids the uncertainties inherent in scattering measurements by working with the shadows of individual particles. It has been used with success to measure size spectra in a range of meteorological environments, from precipitation to contrails. The source is usually, but not always, a laser, and the beam, after traversing the medium, is imaged on a photodiode or a linear array of photodiodes. Typically, three optical channels are used, with different magnifications. With a diode array, appropriate logic counts the number occulted and rejects false events. The single-diode device measures the loss of light due to the shadow. This device is a prime candidate for the large probe. In addition to its scientific advantages, it requires only small windows because the light is always highly collimated. To avoid a heavy load on the telemetry, only the first few moments of the size distribution should be transmitted.

Aureole and Extinction

A simple photometer, whose field of view is a vertical slit, can make a number of useful measurements of the cloud above the probe. Its field should be scanned around an almucantar by the spin of the probe and should cross the sun. Attenuation of the direct light gives the extinction of the cloud and the aureole, or bright haze around the sun. Any "lumpiness" detected in the rest of the scan gives information on inhomogeneity of the cloud, as will any departures from smoothness of the extinction.

Solar Flux

A flux sensor should have a hemispherical field of view and a cosine response to measure the total downgoing radiation. Preferably, a similar sensor should measure the upgoing radiation; the difference gives the energy deposition. A broad wavelength range is desired (3000 to 10,000 A and hopefully up to 30,000 A).

Nephelometer

Scattering of light does not give specific information about cloud particles, but it is useful as a backup and as a cloud-presence indicator. The source could be a gaseous discharge, external to the pressure vessel, or an internal diode laser with a very small window or light pipe. Modulation of the source permits discrimination against natural light. A sensitivity of 10^{-6} cm^{-1} (scattering coefficient) is readily obtained and is enough to observe Rayleigh scattering by the gas at 1 bar pressure. This instrument is considered secondary on the large probe, but primary on the small probes.

Infrared Radiometer

A measurement of the flux of planetary radiation is considered desirable. A simple, chopped, internally-calibrated instrument can be produced from off-the-shelf components. The principal problem is the window, which must transmit the required wavelength band, be kept free of condensate, and have its temperature monitored so that its thermal emission can be subtracted from the measurement. The details will depend on the design adopted, but no fundamental problems are seen. One possibility is to use several narrower wavelength bands instead of one broad one.

Omitted Instruments

In the following we list, with brief explanations, a number of instruments that were considered, but not included in the final selection. Some of them are from the NAS Venus Study and the rest came to our attention in various ways.

(1) Wind-drift radar - This instrument was omitted because its function appears to be fulfilled by Earth-based radio interferometry. It should be studied further in case it is needed later. It has been judged feasible for heights less than 25 km.

(2) Magnetometer - This instrument is included on small probes, but omitted from large probe so that requirements for magnetic cleanliness can be relaxed.

(3) Condensimeter-Evaporimeter - This instrument was meant to be the Venus analog of a frost-point hygrometer. No suitable candidate instrument exists, to our knowledge, and the need is not great.

(4) Nuclear Fluorescence - Alpha particles or X-rays are widely used for chemical analysis of solids by excitation of fluorescent radiation.[1] Detection seems to require a thin window, which cannot be a thermal insulator; the required high-temperature detectors do not exist. If these problems can be solved, the methods have promise for measurement of particles and, in the future perhaps, of the surface composition.

(5) "Kyle Boiler" - This device is used for measuring water content of terrestrial clouds from the heat necessary to cause evaporation. It does not appear to be specific enough nor sensitive enough for use in an exploratory situation.

Targeting Strategies

The first main probe should enter on the day side of Venus in the region of the equator, not closer than 20° to the terminator. Without this constraint, the sun would be too low in the sky for the solar radiometer.

The primary target of the second launch will probably be on the night side of Venus. However, if the first mission should fail, we expect that the science teams will request a retargeting back to the day side for a backup, unless the cost to the mission is unacceptably high.

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1 Turkevich, A.; Economou, T.; Franzgrote, E. J.; and Patterson, J. H.: Some Preliminary Considerations on the Use of Alpha Particles for Analysis of the Atmosphere of Venus. Private Communications, March 24, 1972.

SMALL PROBES

Scientific Objectives

The lower atmosphere of Venus is strongly influenced by large scale motions of the atmosphere. (See Appendix 2.) To understand such motions requires a three-dimensional picture of the driving forces and the atmospheric response. The objective of these small probes is to obtain such a picture.

Weight limitations clearly do not permit the elaborate instrumentation of the main probe. However, a combination of many measurements on the main probe and a few measurements at other locations is a very powerful approach, provided that the small probes are reasonably well separated.

From existing theory, we anticipate that the important motions have a global scale. Their forcing is either from day to night hemisphere above the clouds or from equator to pole well below the cloud tops. In the lower atmosphere we do not anticipate instabilities with a high planetary wave number, nor do we anticipate large local variations caused by variable solar heating in the clouds. Under these circumstances a few observations, separated by significant proportions of the equator-to-pole or sub-solar to anti-solar distances, can illuminate some of the important physics and dynamics of the lower atmosphere.

This point of view is emphasized in the NAS Venus Study and we strongly endorse it. Even though the small probes carry only a small science payload the few instruments that can be flown are essential to the overall mission.

The simplest and most important contributions to understanding the dynamics can be made by measuring the temperature as a function of pressure and the wind velocity itself. Temperature measurements must be accurate, but the required accuracy can be achieved without serious difficulties. (See Appendix 2.) Wind measurements are feasible because of the development of very long base-line interferometry (Appendix 5) provided that the small probe oscillator is sufficiently stable or a turn-around transponder can be carried.

An accelerometer provides a backup to both wind and temperature measurements and is a valuable diagnostic tool. Most of the small probes will enter in darkness and only a nephelometer can give information about the clouds. Although the information from a nephelometer is not refined and cannot be analyzed in terms of particle sizes nor give any information on cloud composition, the data available from the main probe, taken together with the local temperature and pressure measurements from the small probes could lead to an understanding of the observed cloud layers. Despite the relative homogeneity of the atmosphere, we cannot be confident that the clouds will be identical in different parts of the planetary circulation. A nephelometer is therefore an important instrument.

Finally, a magnetometer is recommended for the small probes for both practical and scientific reasons. The vector magnetic field must be measured at a number of locations to establish its character. The three small-probe locations would be valuable in this respect. Equally importantly, the small size of the probes, and the absence of a mass spectrometer, make magnetic cleanliness relatively simple to achieve.

Candidate Payloads

The six instruments listed in Table 3 are all desirable and feasible. They are all rated category "A". The figures in parentheses represent a priority order within the "A" category. The estimates of power and bit rate are below those assigned in early studies of the mission. They do not appear to give rise to any difficulties with the payload. The weight of the candidate payload however exceeds by about 50% the earlier estimates.

Table 3. Payload and Priorities

Instrument	Weight (lb)	Power (Watts)	Bit Rate (bps)	Priority Category
Temperature	1.0	0.2	0.4	A (1)
Pressure	1.0	0.75	0.4	A (1)
Nephelometer	1.5	1.0	2.0	A (2)
Stable Oscillator	1.5	1.5	---	A (3)
Accelerometer	0.4	0.4	0.2	A (4)
Magnetometer	1.2	1.0	0.1	A (4)
TOTALS	6.6	4.85	3.1	

The payload of the small probes is very difficult to estimate at this time. We believe that further studies may show the candidate payload to be acceptable. We strongly recommend that all instruments be flown if at all possible. In view of the weight restrictions, however, it is possible that the whole complement cannot be flown. The priority listing is for this eventuality. It was the opinion of the SSG that, while the two highest priority instruments constitute a valuable payload, it would be difficult to justify the small probes if only these instruments could be flown. We therefore specify the temperature, pressure, and nephelometer as the minimum payload required to justify the small probes.

Individual Instruments

Temperature, Pressure, and Acceleration

For a description of these instruments, refer to the discussion under the large probe.

Nephelometer

This instrument measures scattering power per unit volume at a single angle of scattering or an average over a range of angles at a single wavelength. The purpose is to establish the presence of clouds, if the scattering exceeds molecular scattering, and to make estimates of the cloud density.

Nephelometers have been used for similar purposes in terrestrial applications for many decades. They have been successfully flown on aircraft on many occasions since World War II. We regard a simple version as feasible for use at any level in the Venus atmosphere.

One concept involves a pulsed Hg source outside the spacecraft, a small window (less than 1 cm), and a photo-diode inside the spacecraft. The simplest geometric arrangement uses back-scattered light which, while not ideal from the point of view of quantitative interpretation, would achieve the mission objectives. The detector could also monitor the unpulsed, steady background and act as an illumination meter for day-side probes. A more detailed discussion of the nephelometer is provided under the large probe instruments.

Stable Oscillator

Studies of stable oscillators are under way for the small probes. If the frequency can be reconstructed to 1 in 10^9 over a period of one hour, MIT studies indicate that the DLBI and Doppler shift capability can be used to give a sensitive measure of the wind in three dimensions. (See Appendix 3.)

Such frequency reconstruction was achieved by the Venera probes and could be readily achieved on the Pioneer probes if a surface calibration can be employed. This involves receiving a signal from a stationary probe on the surface and it cannot be guaranteed. However, it appears that the temperature of the crystal is the only critical parameter and this can probably be measured and transmitted with adequate accuracy for the required frequency reconstruction.

Crystal oscillators have been subjected to entry shock, and this does not appear to be a problem area.

The problems associated with a stable oscillator have not all, at this time, been solved. Rapid progress is being made, however, and once proved in the laboratory we see no additional difficulties in the space environment since the components involved, crystals and thermometers, are well understood and spaceworthy.

Magnetometer

Magnetometer scientific requirements are described in Appendix 5. The small probes are required to rotate at a few rpm - the speed is not very important - and the single axis of the magnetometer is tilted with respect to the rotation axis. This arrangement makes it possible to determine the vector magnetic field with respect to a directional asymmetry in the antenna pattern.

Magnetic cleanliness at the magnetometer of 10 gamma is required. Because of the small size of the small probes, the cost in special components and design is minimal; the Pioneer-Venus Project has estimated that an upper limit of $200,000 will be adequate for the magnetic cleanliness program.

Other Instruments

Two other instruments were considered, but not recommended. A surface approach indicator was considered to be unnecessary. The small probes are atmospheric probes and fulfill their mission if they survive close to the solid surface. The science value of locating the surface exactly at a few points is not large. We did not therefore consider this instrument to be worth a significant cost in money and weight.

Also, because it is very difficult to avoid targeting at least two of the small probes to the night side, at least for the 1976/1977 mission, a solar radiometer would be wasted on two or more of the small probes. Since the nephelometer provides data on the presence of clouds, we considered a solar radiometer to be redundant. We do not recommend its inclusion in the small probe payload.

Targeting Strategies

The following factors should be considered when targeting the small probes:

(1) The existing state of knowledge does not enable us to distinguish between the atmosphere in the Northern and Southern hemispheres. Thus, the strategy should aim to obtain the greatest coverage in longitude and latitude independent of the hemisphere. If it should be convenient, for example, to place all four probes in one hemisphere, this would be an acceptable result.

(2) The minimum spread in latitude should be 0 to ±30°. This covers one-half of the area of one hemisphere. This spread should be achievable without difficulty and would be the minimum acceptable for studies of the planetary circulation. A spread of 0 to ±60° would be sufficient for most dynamical problems. It may be difficult to achieve and is the limit of what should be attempted.

(3) The minimum spread in longitude is 90°; 120° can be taken as an upper limit that need be attempted.

(4) There is no requirement to target the small probes into sunlight.

(5) It would be valuable for the DLBI project if all probes could enter within about 30 minutes of each other.

THE BUS

Scientific Objectives

The bus provides a platform for measurements in the upper atmosphere and ionosphere. It permits measurements in a region below orbiter minimum periapsis that will not be explored by the entry probes. Measurements include the ionospheric magnetic field, the solar wind, the interplanetary magnetic field, electron, ion, and neutral particle densities.

The payload weight available on the bus is limited so that it was not possible to include measurements which could be made as well or better from the orbiter or were not required to enhance the objectives of other probe mission experiments. However, those instruments were included in the payload of the bus which return useful information in the interplanetary medium as recommended by the 1970 NAS Venus Study. ("Measurements made in the solar wind are valuable for their own sake and should be regarded as secondary objectives that significantly enhance the value of the mission.") The measurements which should be made from the bus are discussed below. The recommended instruments for making these measurements, together with a rationale for their selection, are discussed in a later paragraph. We note that these experiments and measurements are not independent of one another nor are the bus and probe measurements completely independent.

In the upper atmosphere, we recommend measuring the number density of selected neutral constituents; for example He^4, O, CO, N_2, Ar^{40}, CO_2 should be measured with a mass spectrometer and CO, and O should be measured with a UV fluorescence device. The UV fluorescence measurement removes the ambiguity between the N_2 and CO peaks and provides a redundant O measurement. Also, the number density of light ions and the number density and temperature of electrons should be measured. While these are the direct observables, they will provide other information. The scale heights, for example, provide a measurement of the temperature of the neutrals and ions. Knowledge of the neutral-gas and electron temperature and density allows a calculation of the cooling and heating rates to be made. The ratio of the Ar^{40} concentration relative to that of N_2 will lead to a determination of the position of the turbopause. The CO, O, and CO_2 concentrations provide information on the photochemistry of CO_2.

To complement the probe magnetometer measurements, we recommend that the bus carry a triaxial vector magnetometer. The bus and probe magnetometers can be used to determine ionospheric currents and thus separate ionospheric and planetary magnetic fields in the probe data. The bus data will provide information on the magnetic term in the ionospheric pressure tensor and aid in calculation of electrical conductivities in the ionosphere.

We recommend measuring the solar-wind proton velocity, density, and temperature and the interplanetary magnetic field. These quantities, in turn, provide a measure of the electric field capable of driving ionospheric currents and the solar-wind pressure confining the ionosphere. Away from Venus these same quantities will provide new and important data. Since there will be two launches, we can study the evolution of solar-wind structure, during an interval of several hours.

Candidate Payload

A payload consisting of Category "A" and "B" experiments is necessary to satisfy all the objectives listed above. However, such a payload exceeds the nominal bus payload weight. We have therefore placed solar-wind measurements in a lower category since these are a secondary objective for a probe mission.

Experiments were recommended by the 1970 NAS Venus Study which do not appear in our recommended payload. We note that 1970 payload was oversubscribed by 19 pounds. The basis for deletion was either that an experiment was more appropriate to an orbiter or that it was redundant. The candidate payload is listed in Table 4. The weights given in this table are those for similar instruments used in the terrestrial environment. Each of these experiments and those deleted from the 1970 NAS Venus Study report payload are discussed briefly in the following paragraphs.

Table 4. Recommended Payload for 1976/77 Bus Mission

	Priority Category	Weight (lb)	Power (Watts)	Data Rate (bps)	Measurables
Neutral Mass Spectrometer	A	10	10	80	Neutral atmospheric composition; scale height.
Ion Mass Spectrometer	A	3	2	70	Ion composition; scale height.
Langmuir Probe	A	2	2	30	Electron temperature and density.
UV Fluorescence*	A	3	2.5	50	CO, O density.
Magnetic Field	A	6†	3.5	30	Vector magnetic field.
Solar Wind	B	5	4.0	40	Solar wind ion density, velocity and temperature.
Dayglow	C	3	2.5	50	Composition of neutral atmosphere.

* Flight testing of this instrument in the terrestrial environment is not complete at this time. If tests show this experiment is not suitable for this mission, alternative experiments should be considered to satisfy the objectives of this instrument.

† Includes weight of boom.

Individual Instruments

Neutral Mass Spectrometer

The neutral mass spectrometer will determine the number density of selected constituents of the upper atmosphere, for example He^4, O, CO, N_2, Ar, and CO_2. Parameters derived from these measurements as a function of altitude include the exospheric temperature and the altitude of the turbopause. The latter measurement can be achieved by measuring the Ar/N_2 and He/N_2 ratios. The combination of the neutral and ion mass spectrometers will permit detailed analysis of the chemistry of the Venus upper atmosphere. The CO and O measurements will permit a study of the intriguing stability of CO_2. It may be possible with careful design to measure the O concentration within a factor of 2.

Similar experiments performed in the terrestrial thermosphere have shown that He, N and Ar in the range of 10^7 to 10^{12} cm^{-3} are reliably measured by fast scanning mass spectrometers. Because of the low anticipated bit rate and fast descent of the spacecraft, attainment of a reasonable altitude resolution will require special considerations for instrument design and efficient data management.

Ion Mass Spectrometer

The ion mass spectrometer should measure the number density of selected thermal ions in the upper atmosphere of Venus, for example H^+, D^+, He^+, O^+, CO^+, NO^+, O_2^+, and CO_2^+. Although a primary objective of the bus mission is to study the region below 200 km, the instrument's sensitivity should be chosen to measure the ionopause. Efficient data management techniques will be needed to maximize science return in view of the limited bit rate and the rapid entry velocity of the bus. The scale height of the ionic species together with data from the Langmuir probe and neutral mass spectrometer will provide absolute ion densities and ion temperatures. They will permit a study of both the chemical and physical processes in the upper atmosphere of Venus.

Langmuir Probe

This experiment measures the temperature and number density of the ionospheric thermal electron population. The technique is simple, lightweight, and accurate. A secondary benefit is a measure of spacecraft potential which is both a useful plasma parameter and an aid in interpreting the ion spectrometer data. These data in combination with the data from the neutral gas and ion spectrometers allow chemistry and energy balance calculations of the Venus thermosphere and ionosphere.

UV Fluorescence

This experiment will measure the amount of O and CO in the upper atmosphere of Venus. This measurement is a backup to the neutral mass spectrometer for two very important minor constituents. It will lead to a better understanding of the chemical processes affecting the dominant constituent of the upper atmosphere CO_2. In particular, it should help to solve the mystery of the stability of the CO_2 to photolysis. The instrument utilizes fluorescent backscatter of light from an onboard source. It is in routine use in laboratories and is being tested in rocket flights. Its inclusion in the payload is dependent upon the success of these tests. The instrument is sensitive to the Doppler shift of spectral lines by the entry velocity of the bus. Thus, measurements must be made with the direction from the light source at right angles to the velocity vector. A deep penetration of the upper atmosphere is highly desirable for this experiment.

Magnetometer

The magnetometer should be a triaxial vector instrument of rugged design. A three-axis measurement is recommended to provide unambiguous vector measurements in the turbulent sheath surrounding the ionosphere as well as providing for accurate boundary normal determinations. The magnetometer should be capable of resolving expected planetary fields above 100 km altitude and should have enough sensitivity for interplanetary measurements.

Because the emphasis of a probe mission is on the upper and lower atmosphere, magnetic cleanliness procedures usually performed for interplanetary missions cannot be allowed to jeopardize the main objective or increase costs. Thus, the magnetometer will be subject to a significant ambient magnetic field from the spacecraft.

The primary objective of the magnetometer is to measure the ionospheric magnetic field. This complements the small-probe measurements below the ionosphere. The combination of measurements could provide a measure of both the planetary and ionospheric fields. Secondary objectives include measurements through the bow shock, sheath region, and the ionopause. The latter magnetic profile has not been previously measured. A further objective is the study of the time evolution of interplanetary structures made possible by the dual launch.

Solar Wind Experiment

The primary objective of the solar wind experiment will be the measurement of solar wind velocity, density, and temperature acting on the Venus ionosphere at planetary encounter. A secondary objective of the experiment is measurement of the solar wind during the cruise phase of the mission. The dual launch permits a study of the evolution of solar wind structure over a corotation delay of several hours. Design of this instrument is facilitated by a spin-axis orientation perpendicular to the eliptic plane, but other orientation can also be accommodated.

Dayglow Experiment

A dayglow experiment could be dedicated to a number of specific neutral constituents of the Venus atmosphere, for example H, D, He, and Ar. This technique is a more powerful tool for probing isotopic ratios than for absolute densities. The measurement of the H/D ratio is important and ideally suited to this technique, but was not recommended because it could be easily handled from the orbiter. The measurement of He density is important, but can be achieved with higher accuracy with the neutral mass spectrometer. The Ar^{36}/Ar^{40} ratio is an important parameter in models of the evolution of planetary atmospheres. Ar is measured by the mass spectrometer, but a dayglow experiment could provide an unambiguous backup measurement of the Ar^{36}/Ar^{40} ratio on the probe mission.

Other Instruments

A Retarding Potential Analyzer was listed as an alternative to a Langmuir probe in the NAS Venus Study payload. The Langmuir probe was preferred because the scale height measurements by the neutral spectrometer, ion spectrometer, and Langmuir probe combined with the electron temperature data from the probe should provide unambiguous ion and electron temperature profiles.

AC electric field measurement was deleted from the NAS Venus Study payload even though it was an important cruise mode experiment, and could aid in the understanding of the ionospheric and atmospheric processes on Venus. It was judged to be more effective if flown on the orbiter.

A UV Spectrometer was also not recommended because its major objectives could be more readily achieved on the orbiter.

Visual imaging, in the form of a spin-scan camera, was mentioned in the NAS Venus Study. It could be of value for determining motions near the cloud tops and could yield information on cloud forms. For the imaging to be effective, however, cloud forms or groups must be identifiable; this may not be the case. There is, in fact, a weak consensus that the Venus clouds are more like a terrestrial haze than cumulus or other clouds with identifiable features. This question will be clarified by the Mercury/Venus fly-by. If great interest is thereby created in visual imaging, there will be ample opportunity to review priorities on the orbiter and to include a spin-scan camera in the payload.

Targeting Strategies

The advantages of a low-altitude fly-by versus an impact trajectory were discussed at length. A fly-by would provide measurements of horizontal or local time variations and provide two radio occultations. This approach, however, risks losing data at the lowest altitudes because of the uncertainties inherent in the pre-encounter knowledge of the trajectory. An impact trajectory would guarantee a passage through a region below 200 km which could not be sampled by the orbiter. These data are very important to an understanding of basic ionospheric processes and the bus should penetrate as low as possible.

For the first mission, it is recommended that the bus enter close to the entry point of the large probe. For the second mission, the selection of the entry point should remain contingent on the results of the first mission.

To provide a DLBI reference point on a known ballistic trajectory, it is recommended that enough fuel be carried to guarantee that the bus will have the ability to remain above the atmosphere and in the same field of view as the entry probes during the first hour of entry. If possible, the bus should not enter the atmosphere until the probes have reached the surface.

INSTRUMENT DEVELOPMENT AND ASSOCIATED TECHNOLOGY

The concept of Pioneer-Venus is based in part on the practical notion of conducting significant exploration and study of Venus on a modest and predictable cost basis. Accordingly, designs of the spacecraft and instrument complements must use established techniques and involve engineering approaches which do not require significant advances in the state-of-the-art. It is recognized that modification of established instrumental techniques and components will be required to accommodate the very demanding interface of the entry spacecraft. Following this concept, the typical payloads described in this document have been selected and defined recognizing that long lead-time engineering will be required in some cases, but assuming that critical developments will not be necessary. All components will thus be derivatives of instrument elements already proven in space.

Recommended Long Lead Development Items

The following list of items is considered appropriate for early development, because in our opinion they will be required regardless of ultimate science instrument selection. The Pioneer-Venus Project Office is urged to undertake these tasks to the extent feasible, prior to selection of flight instruments, and thereafter, as necessary during the Phase B System Design Study. The tasks fall into the following four categories:

(1) Verification of performance and system compatibility of alternative approaches to certain high-priority experiments to establish a firm engineering base for experiment selection. These experiments include:

- Neutral Mass Spectrometer for the Large Probe. Several alternate approaches to inlet design are under consideration. At this time, it appears most desirable for the Project to support continuation of the ongoing engineering studies and tests to permit early selection of the most suitable inlet and inlet/probe interface.

- Transponder/Stable Oscillator for the small probes. It is necessary to the development of an optimum DLBI program that a sound tradeoff study be made between these two approaches to frequency stability or prediction.

- DLBI/Wind Drift Radar. On the basis of present knowledge, the DLBI appears to be the more cost effective approach to wind velocity measurements. The relative data upon which this choice was made should be further refined by a detailed engineering study. This study should evaluate the operational costs and impact on ground-station operations and mission design of DLBI. It should further evaluate feasibility, costs, and performance tradeoffs of candidate wind-drift radars.

- RF Experiments on the Orbiter. A systems-level study, required to determine the best way to implement the RF Occultation, bistatic radar, and RF altimeter, has obvious impact upon the design and selection of these experiments and should be conducted at the earliest possible time.

(2) Engineering studies of high-priority experiments to define interface requirements and system design criteria in support of the Phase B System Study. Instruments having large impact on system design include:

- Cloud Particle Size Spectrometer. A large probe experiment, which poses stringent requirements for optical alignment of external hardware.

- Solar Flux Detector. A large probe experiment, which requires simultaneous upward and downward viewing.

- Nephelometer. A small probe experiment on which the viewing requirements and packaging configuration will require careful and early definition.

- Magnetometer. A small probe experiment, which requires a careful program to achieve reasonable magnetic cleanliness and stability at low cost.

- Ultraviolet Fluorescence. A bus experiment for CO and O, which is on the verge of being qualified for flight.

(3) Continuing feasibility studies of instruments considered desirable adjuncts to science payloads, but assigned lower priorities because we cannot establish, with high confidence, the development status, performance capability, or system or mission compatibility. These are:

- Hygrometer. At least one candidate instrument appears to offer the potential for satisfactory performance in the Venus atmosphere. This requires verification by suitable environmental tests, clearly beyond the scope of SSG activities.

- IR Flux Detector/IR Radiometer. A number of candidate instruments were considered, but in each case several questions concerning feasibility remain to be answered. The Project Office should support suitable efforts to resolve these questions prior to the time of selection.

- X-Ray Fluorescence Spectrometer. Lack of sufficient information on existing instrument design and performance prevented inclusion of this instrument on the large probe payload. The Project Office should support further definition of this potentially useful means of investigating atmospheric particulates.

(4) Continuing engineering of hardware, interface design, and operational procedures, the early development of which significantly impacts experiment design and selection, system design, or program costs. These include:

- Optical Windows and Window Protection. A detailed parametric evaluation has been carried out by the Project Office to determine the electrical power required to maintain the temperature of the window above that of the ambient environment. It was determined in the course of this study that the dominant factor controlling the amount of required power is the supporting tube conductance which to a first approximation is proportional to the ratio of its thickness to length. In the case of the one-inch diameter window, it was found that 4.5 watts continuously applied from parachute deployment will provide the required temperature response. This exceeds the amount of power available on the small probe. Accordingly, windows of smaller diameter were investigated. For a 1/4 inch diameter window, it was found that 1 watt will maintain the window above ambient temperature to an altitude of 10 km. Verification of these calculations by test is necessary; therefore, facilities to provide the required simulation of the descent temperature-pressure profile are now being fabricated at Ames Research Center. At this point in time, it appears that any experiment requiring the use of a window on the small probe is feasible from the contamination standpoint. Various approaches to prevention of obscuration by particulates collecting on windows are also being studied. The Project Office should pursue these tasks with high priority to facilitate experiment selection and design.

- Small Probe Heat Shield Technology. The minimization of heat shielding weight is of critical importance for the small probe because the nominal scientific payload of 3 pounds represents an extremely small fraction (0.06) of the entry weight. The SSG recommends that every attempt be made to optimize the small probe heat shield design considering specifically the factors summarized below:

  - Choice of Material. During the course of the Phase B study, the contractors will investigate, in detail, the possibility of using the reflecting heat shield concept (e.g., Teflon) currently being examined at Ames Research Center. Initial calculations show that by using this approach, a weight saving of 1/2 to 1 pound could be realized. This could be increased to 2-1/2 pounds by going to a more efficient material such as one of the dielectrics having a higher sublimation energy than Teflon.

  - Selection of Factor of Safety. Existing designs, which are based on the traditional spacecraft approach, are extremely conservative with contingency margins that range from 1.3 to 1.5 with a corresponding maximum weight penalty of up to 1.95 pounds. Proceeding in the spirit of the test philosophy adopted for the qualification testing of Pioneer-Venus subsystems, the contingency margin should be reduced to the order of ten percent. The final choice should be based on a re-examination of the heat shield performance sensitivity to environmental and material property uncertainties.

  - Establishment of Broad Data Base. Tests in the Ames Research Center facility should be conducted during the Phase B study at heating conditions simulating those expected during Venus entry. This testing should evaluate candidate materials and validate the computer program for the design.

- IR Windows. A study of suitable windows for IR instruments is being conducted by the Project Office. This effort should be continued on a high-priority basis to support IR experiment design and selection.

- High-Temperature Components. A family of electronic components and power sources which appear capable of operating at Venus surface temperatures have been identified by the Project Office. The technology should be carefully investigated for possible application to the 1976/77 mission and as a potential long-lead development task for the 1980 probe mission.

Science Procurement Considerations

The Role of the Principal Investigator

The concept of a Principal Investigator for each experiment on the Pioneer Venus missions is strongly endorsed by the SSG. The Principal Investigator should assume primary technical responsibility for the development and production of the instrumentation for his experiment. He may elect to have the Project Office assume administrative responsibility for hardware procurement. In some cases, where instrument-spacecraft interface is close and complex, such as on the small probes, it may be essential that the instruments be developed as a single integrated subsystem by the Project Office. This does not, however, obviate the need for scientific direction of each experiment by a Principal Investigator.

Parallel Development

In several important areas, the SSG's survey of candidate experiments has identified more than one instrument approach offering good potential for satisfying measurement requirements. In cases where the choice between alternatives has significant impact upon system design, experiment selection for flight, or costs, the SSG recommends pursuit of parallel development of the most promising alternatives to the point where a sound selection can be made.

Cost Considerations

Effective cost management of Pioneer-Venus science requires a comprehensive program that begins with selection of experiments on the basis of specific and well defined specifications, and planning on the basis of realistic budgets for interface and cost, and continues throughout instrument development to final data analysis. Negotiations for contract or work agreements must, in turn, be based on realistic budgets, rather than on a concept of setting artificially low baseline budgets for interface (weight, power, telemetry, etc.) and costs in the hope of holding down eventual final costs. Once established, such realistic budgets must be strictly enforced, if necessary, by relaxing the objectives or testing requirements. In this connection, we call attention to a recommendation of the NAS Venus Study on "Achievement of Minimum Cost" and to the cost control paragraph in Chapter 1 of this document.

To accomplish the ambitious science objectives of Pioneer-Venus within the cost constraints, the use of certain nonstandard practices may be necessary. The Project is urged to evaluate the cost advantages of performing certain engineering tasks in-house at Ames Research Center or other NASA Centers, and to carefully assess the real need, on this program, of conventional practices whose value cannot be firmly demonstrated. These latter elements can include nonessential quality assurance provisions, reliability studies, large safety factors in design and test, unnecessary drawings and documentation.

Testing Procedures for Entry Probes

The large and small probes are specifically atmospheric probes. They are intended to explore the atmosphere from a pressure level of approximately 50 mb to the solid surface of the planet. There is, however, no requirement for these probes to survive on the surface nor even to guarantee instrument survival up to impact under extraordinary conditions -- such as landing in a deep rift.

We do not anticipate important boundary layers close to the solid surface and we expect the lower atmosphere to be substantially homogeneous. Thus, while we place great emphasis on measurements of the atmosphere in the lowest two or three scale heights, it is not essential to have data from each kilometer of this region.

As a consequence of these limited objectives, the SSG believes that it is sufficient to test the probes under conditions substantially equal to the mean surface temperature and pressure (770°K and 100 atmospheres). (See Appendix 6.) For example, from the point of view of the scientific return, a probe giving results to 90 atmospheres would be a complete success even in the absence of impact. We have no requirement from an atmospheric viewpoint of knowing the location of the surface to an accuracy greater than it is now known. It is for this reason that surface approach indicators have been omitted from both large and small probes.

While surface survival is not a requirement for the mission, it may nevertheless occur for seconds or even minutes. We believe that it is prudent to take account of this possibility. On the main probe the accelerometer should, therefore, be designed to have the capability of a mini-seismometer, in accordance with the view expressed in the NAS Venus Study. We have also taken account of the feasibility of a calibration of the small probe stable oscillator in the manner of Venera 7. We wish to re-emphasize however that this does not amount to a requirement for surface survival and that we do not require testing to pressures or temperatures greater than the mean values.

Chapter 3

1978 AND 1980 MISSIONS

PROPOSED MISSION SEQUENCE

Table 5 summarizes the views of the NAS Venus Study; however, the launch dates have been set back one opportunity. The rationale for this sequence is given in the study report and has been reviewed by the SSG. The SSG makes the following recommendations.

(1) We endorse the NAS recommendations for the first three missions, including the recommendation that the multiple-probe mission should be dual but not subsequent launches. We give details of a typical payload for the second, orbiter mission.

(2) The third mission should not involve a redesigned spacecraft. Although the large probe in the multiple-probe mission is not required to survive on the surface, we nevertheless anticipate that it will do so, and that modifications within the same spacecraft design will give a surface survival lifetime sufficient for planetological experiments. This expectation will be confirmed or refuted by the 1976/77 mission. The 1980 mission should not be firmed up until these results are available.

(3) We make no recommendations about the 1982 mission. There is reason to believe that cooperation with ESRO and with the Soviet space program may impact planning at this stage.

(4) We strongly support the NAS recommendation that Pioneer-Venus be regarded as a continuing program with launches at essentially every opportunity.

(5) The NAS Venus Study states:

> "We note that eventually the sequence of controlled and modest observations can lay the basis for a more ambitious series of probes of the orbiter-lander class. We endorse the concept which the Planetary Explorers (Pioneers) express of preparing for such an elaborate venture with a well-thought-out series of preliminary observations carried out with moderate resources."

We accept this statement as a responsible view both of a mature scientific program and of the need for program strategies which are compatible with those of other disciplines, as emphasized by the 1970 NAS study Priorities for Space Research 1971-1980.

Table 5. SSB (1970) Recommended Sequence

Mission	Date	Description
Multiple-probe	1976	Atmospheric emphasis. Dual launch. Bus, main probe, and three small probes.
Orbiter	1978	Aeronomy; particles and fields; imaging and radar.
Survivable Probe	1980	Crustal composition; seismicity; atmospheric pressure, temperature, and winds.
Balloon	1982	Tentative. Two sets of three balloons at 50,500 and 1200 mb.
NOTE: All launches single except for 1976.		

1978 MISSION

The 1978 orbiter mission will be the second of the Pioneer-Venus series. The mission will consist of a single, spin-stabilized, solar-cell-powered spacecraft launched during May or August 1978 by a Delta 2914 launch vehicle. If launched during May, the spacecraft will fly a 200-day trajectory to Venus and arrive in December. The launch weight will be about 625 pounds and the weight in orbit about 415 pounds (assuming a 24-hour orbit period). If launched during August, the spacecraft will fly a 120-day trajectory to Venus and arrive in December. The launch weight will be about 735 pounds and the weight in orbit about 395 poinds (assuming a 24-hour orbit period).

The cruise from Earth to Venus will include two or three midcourse maneuvers to control the trajectory. During cruise, the telemetry bit rate will be about 16 bits per second. The orbiter experiments will weigh from 50 to 70 pounds and consume about 25 watts of power. The spacecraft will initially be placed in an orbit with periapsis altitude of about 400 km. Periapsis will move up and down as the orbit responds to solar perturbations and will be corrected as necessary to remain within acceptable limits. Data will be stored during the periapsis phase of the orbit and replayed when the spacecraft is near apoapsis or as ground stations are scheduled. The data memory will have a capacity of about 5×10^5 bits. Data transmission to Earth will be at rates from about 2000 bits per second to 20 bits per second depending on Venus distance from Earth and the size of the ground receiving antenna used. The design mission will remain in orbit for one Venus sidereal year (225 days).

We have considered the major scientific questions described in the NAS Venus Study, Appendix 1; the information which is likely to have been gained from the multiple-probe mission; and the capability of the orbiter spacecraft.

In our opinion, the principal objectives of the orbiter mission should be as follows:

(1) Global mapping of the atmosphere and the ionosphere by remote sensing and radio occultation to extend the information obtained on the vertical structure from the entry probe mission.

(2) Global studies by "in situ" measurements of the upper atmosphere, ionosphere, and solar wind - ionosphere interaction region to extend and supplement the information obtained with the entry probe mission.

(3) Studies of the planetary surface by remote sensing.

A typical payload complement which can satisfy these objectives is listed in Table 6. Care was exercised in the selection of these experiments to include only flight-tested or well-proven instrumentation in accordance with the general mission philosophy. It is our recommendation that the orbiter be designed to have a tiltable, despun antenna which would be used for telemetry as well as the radio science experiments. The total experiment weight is 81 pounds, which can be achieved with an orbit period of about 24 hours and an apoapsis distance of 6.6×10^4 km for a Type II orbit. It is our opinion that this combination of payload and orbital parameters will optimize the science return of the 1978 orbiter mission.

The plan for a joint Franco-Soviet mission, which is to place three to six instrumented balloons in orbit around Venus in 1978, was brought to our attention. When plans for this mission firm up, the addition of a balloon interrogator (approximate weight is 10 pounds) to the orbiter payload and the use of the DLBI/DSN facilities should be seriously considered by NASA, because of certain parallel and mutually supporting scientific objectives of the two missions.

Table 6. 1978 Orbiter Typical Payload

Instrument	Measurables	Weight[1] (lb)
Radar altimeter	Strip mapping of surface height variations (and geopotential heights), reflectivity and roughness.	20[3] (Radar altimeter, Bistatic radar, Two frequency occultation combined)
Bistatic radar[2]	Surface roughness on a scale of 3.5 to 13 cm; surface reflectivity at various angles of incidence and polarization.	
Two frequency occultation	Temperature and pressure measurements in the lower atmosphere; dispersive absorption and scattering by particles in clouds.	
IR radiometer	Thermal structure of the atmosphere above the cloud tops.	9

Table 6. 1978 Orbiter Typical Payload (Contd)

Instrument	Measurables	Weight[1] (lb)
Airglow and scattered solar light[4]	Typical measurements could include one or more of the following: resonant scattering measurements of the lower atmosphere; resonant scattering measurements to evaluate the H/D ratio; general airglow measurements; occultation measurements.	9
Neutral mass spectrometer	Neutral atmosphere composition and scale height measurements.	10
Ion mass spectrometer	Ion composition and scale height measurements.	3
Thermal and suprathermal[4] charged particle detector	Electron and ion temperature and density measurements; photoelectron measurements.	6
Magnetometer	Vector magnetic field measurements.	9[5]
Electric Field Detector[6]	AC and DC electric fields.	7[5]
Solar Wind Detector	Flux and energy distribution of the solar wind particles.	6
Solar Electron Detector[6]	Tracing solar electrons to establish the connection between the ionosphere and interplanetary medium.	2

1 Estimated.

2 This experiment does not require any additional payload weight beyond that which is necessary for the radar altimeter.

3 This number represents the weight increase due to the addition of the second degree of freedom to the antenna and the added weight of the X-band transmitter, the radar X- and S-band receivers, and other electronics required especially for these experiments.

4 These measurements may require one or more instruments.

5 Weights include boom or antenna weight.

6 If the payload is reduced, these experiments are to be considered lower priority.

The IR radiometer represents a class of instruments. In its simplest form it would measure total thermal emission from the clouds. However, vertical temperature profiles and cloud top pressures are required to understand the 4-day circulation of Venus and instrumentation similar to that on Mariner 9 is desirable. However, the weight and data rate of the IRIS instrument are probably too great to be accommodated on this mission. We recommend that an IR sounder of some type be carried on the mission, provided that it can be designed to be reasonably economical in weight and data rate.

We have not given detailed priorities for the instruments in Table 6, but we indicate that the Electric Field and Solar Electron detectors are less important than others listed. We assume that a more detailed review will be made by a subsequent SSG.

We considered the relative experimental advantages and disadvantages of having the spacecraft spin axis parallel or perpendicular to the ecliptic plane. We found that the parallel spin axis would likely limit the period during which solar wind measurements can be made and would necessarily result in a re-evaluation of the antenna system and the radio science experiments, but that all other experiments could be used satisfactorily with either orientation. This question of orientation will therefore have to be re-examined at some later date, but at this time a spin axis orientation perpendicular to the ecliptic plane appears, in general, to be preferable.

To extend the range of the "in situ" aeronomy and radar altimeter measurements, it is recommended that the periapsis altitude be maintained as low as drag and fuel considerations permit. A low altitude periapsis will also improve the gravitational harmonic and local anomaly studies which use orbit perturbation data. A slow spin rate is desirable for a number of experiments; therefore, the slowest safe spin rate, which is a few revolutions per minute, should be selected. To provide the best possible coverage to both the mapping and aeronomy experiments, a midlatitude periapsis location and a high-inclination orbit are preferred. However, these orbital parameters can only be achieved via a Type II trajectory to Venus which would put the periapsis very close to the evening terminator upon arrival at the planet, and this for many experiments is an undesirable situation. Therefore, the selection of these orbital parameters should also be re-examined at a later date, preferably after the selection of the principal investigators, for this mission.

The data requirements for the orbiter payload, except for the IR radiometer and the radar altimeter, can easily be accommodated within the on-board storage capability of approximately 5 x 10^5 bits, together with real-time communications rates of the orbiter. Most experiments will concentrate their operation near periapsis, representing a time interval of a few percent of the orbital period, thus allowing adequate time for transmission of the accumulated data to Earth. The IR radiometer and radar altimeter together would require the entire core storage capability. Their requirement, however, could be met by time sharing; i.e., allowing alternate orbits to be devoted entirely to the high bit rate experiments. Because of the slow rotation rate of Venus relative to the orbital period (approximately 24 hours) no significant loss of information would ensue by such a time sharing scheme.

1980 MISSION

We recommend that the mission for the 1980 opportunity should be another entry probe. This choice permits maximum use of the results of the first entry probe mission in redirecting or improving the experiment complement. If the first entry probe mission should show that the probe can survive for a certain time at the surface, the 1980 entry probe mission should be modified for extended life and include simple experiments designed to answer some first-order questions regarding the planetary surface and interior without the need for a sophisticated survivable lander design.

Even a very rudimentary measurement of the surface composition would constitute a major advance in knowledge. Some important information on volatiles should be available from the first probe mission because surface and atmosphere must be close to chemical equilibrium. A complete chemical analysis, of course, is greatly to be desired, but information on a few elements such as Si, Mg, Fe, Ca, and Al; or even Si, Fe, and Ca; or K, U, and Th, would provide information regarding the differentiation of the planet and its possible bulk composition. High accuracy is desired but even a 10 percent determination would allow first-order questions to be answered such as:

(1) Is the planet differentiated?

(2) To what extent?

(3) Can it be chondritic in composition?

In addition to fundamental questions regarding the origin and evolution of the planet, a more detailed surface composition analysis would answer questions regarding atmospheric-surface equilibrium. A surface composition experiment is therefore considered high priority and we strongly recommend early action in defining several possible experiments and initiating development. Because of technical and budgeting constraints, we urge that attention be directed to the minimum viable experiment; that is, a lightweight, low-cost instrument that can survive in the Venus environment.

An inexpensive, short-lived passive seismic experiment can be easily developed and would provide useful seismic data, in addition to the background characteristics, if the level of seismicity on Venus exceeds that on the Earth or the moon. Because of the large mass of the planet, high surface temperatures and a probability of considerable outgassing, it is reasonable to assume that Venus is an active planet.

Continuous seismic activity would be an exciting discovery with important implications and a seismometer might also be a useful indicator of wind noise. We therefore recommend the development of a lightweight seismometer that can operate under Cytherean surface conditions for the order of one hour.

Surface lifetime can be extended by two means; the addition of insulating and phase change material; and the development of high temperature components. If the 1980 mission concentrates on lander capability, a large amount of weight will be available from the small probes. The problem will be to make use of this available weight without expensive redesign of the large probe. This factor should be taken into account in Phase B design studies.

Preliminary investigations suggest that many of the necessary lander components could be qualified for operation at the surface ambient conditions of Venus. *It is* recommended that studies be pursued on the feasibility of operating instruments without thermal protection on the surface. *If this* capability can be demonstrated, the possibilities of surface science on Venus might be greatly extended and would require further study.

On the basis of Soviet experience and our own design studies, we have little doubt that the first probe mission will demonstrate the possibility of upgrading the large probe to a lander without expensive redesign. If this should not prove to be the case, however, we recommend a choice between another multiple probe mission, with variations in the instrument complement, or a dedicated mapping orbiter. We would delay consideration of a balloon mission until more is known about the proposed Franco-Soviet initiative in this area.

Appendix 1

FIRST-ORDER QUESTIONS ABOUT VENUS
(R. M. Goody)

The separation into 24 first-order questions is arbitrary and has been made as a basis for examination of different spacecraft. Pioneer-Venus is not a transport system to Venus for the sake of independent investigators. It is intended to address itself to a few grand questions about the planet. The experiments support and complement each other to this end. The following list gives the 24 first-order questions:

1. CLOUD LAYERS. What is their number and location? Variations over the planet?
2. CLOUD FORMS. Are they stratiform, cumuliform, or haze?
3. CLOUD PHYSICS. Opacity? Particle sizes? Number densities?
4. CLOUD COMPOSITION. Chemical composition of the different layers?
5. SOLAR HEATING. Where is the solar radiation deposited?
6. DEEP CIRCULATION. Nature of wind in the lowest 3-4 scale heights? Is there any measurable velocity near the surface?
7. DEEP DRIVING FORCES. What are the horizontal temperature gradients in the deep atmosphere?
8. DRIVE FOR 4-DAY WIND. What are the horizontal temperature gradients in the 10 to 100 mb region?
9. LOSS OF WATER. Has water been lost from the planet? If so, how?
10. CO_2 STABILITY. Why is molecular CO_2 stable in the upper atmosphere?
11. SURFACE COMPOSITION. What is the crustal composition?
12. SEISMIC ACTIVITY. What level?
13. EARTH TIDES. Do they exist and with what amplitude?
14. GRAVITATIONAL MOMENTS. What is the figure of the planet and the higher moments?
15. EXTENT OF THE 4-DAY WIND. What is the vertical and latitudinal distribution?
16. VERTICAL TEMPERATURE STRUCTURE. Is there an isothermal region? Are there other departures from adiabaticity? Structure near the cloud tops?

17. IONOSPHERIC MOTIONS. Could they transport the night-time ionization?

18. TURBULENCE. What is the intensity of turbulence in the deep atmosphere.

19. ION CHEMISTRY. What is the ionospheric chemistry?

20. EXOSPHERIC TEMPERATURE. How does it vary over the planet?

21. TOPOGRAPHY. What features exist? How do they relate to thermal maps?

22. MAGNETIC MOMENT. Does the planet have internal magnetism?

23. BULK ATMOSPHERIC COMPOSITION. What are the major gases, down to the 1% level, at different altitudes?

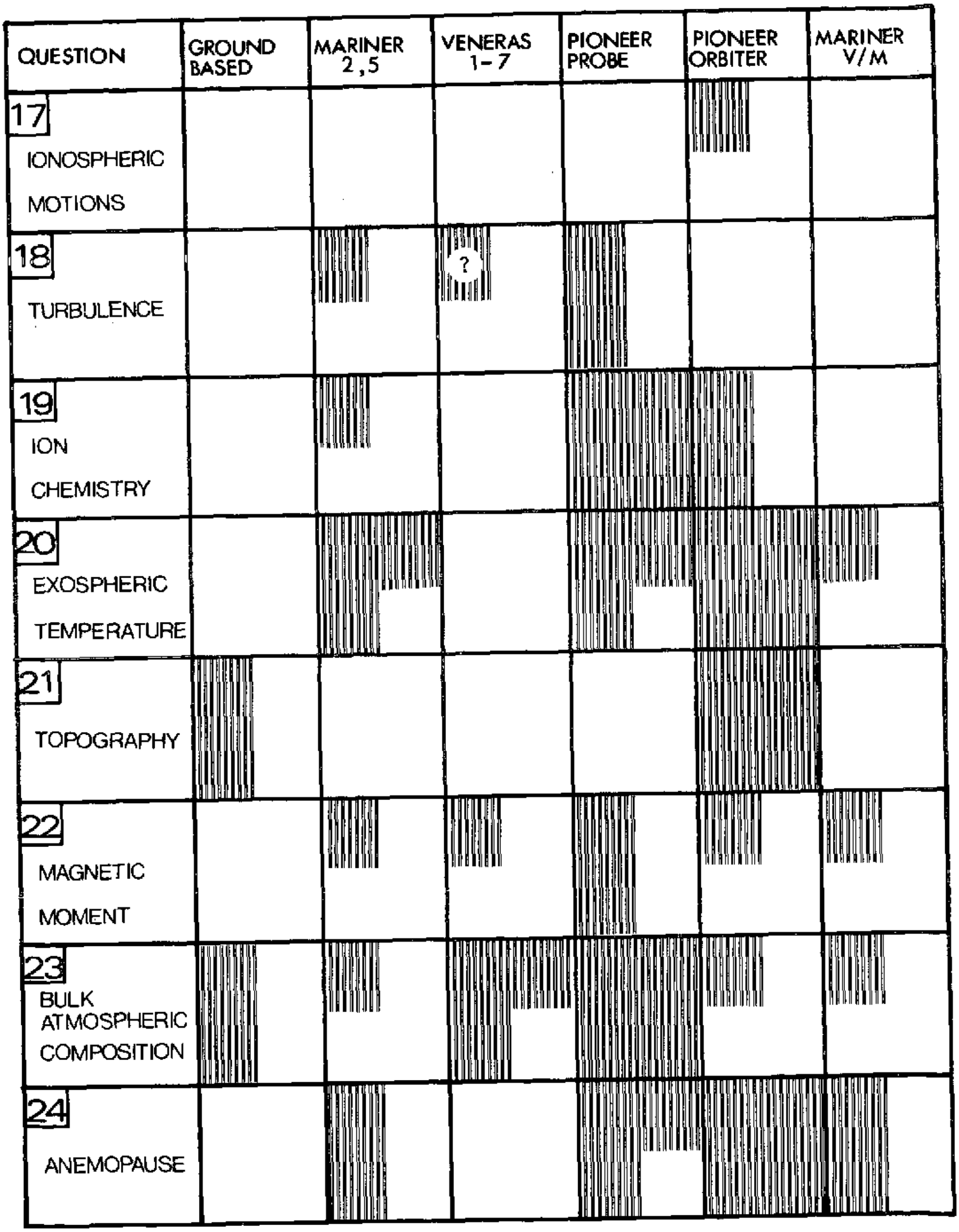
24. ANEMOPAUSE. How does the solar wind interact with the planet?

On the following pages of this appendix, a matrix is used to compare the contributions of the various Venus missions to answering these 24 first-order questions. The last page of this appendix is a summary chart showing comparative mission capability.

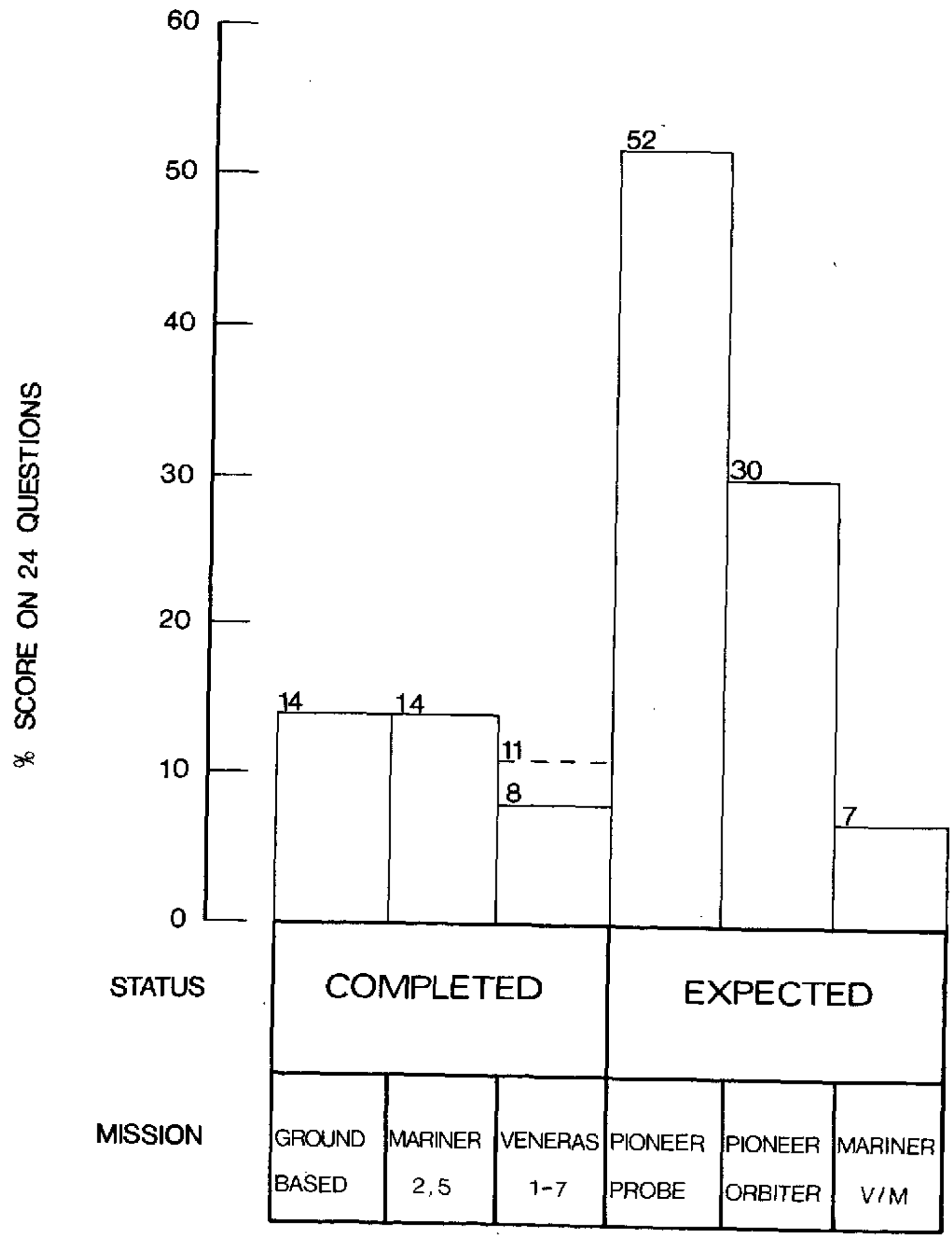
QUESTION	GROUND BASED	MARINER 2,5	VENERAS 1-7	PIONEER PROBE	PIONEER ORBITER	MARINER V/M
1 CLOUD LAYERS	SOME INFORMATION	SIGNIFICANT INFORMATION		SATISFACTORY ANSWER		
2 CLOUD FORMS	SOME INFORMATION			SOME INFORMATION	SIGNIFICANT INFORMATION	SOME INFORMATION
3 CLOUD PHYSICS	SOME INFORMATION			SATISFACTORY ANSWER		
4 CLOUD COMPOSITION	SOME INFORMATION		SOME INFORMATION ?	IMPORTANT CONTRIBUTION		
5 SOLAR HEATING				IMPORTANT CONTRIBUTION		
6 DEEP CIRCULATION			SOME INFORMATION ?	IMPORTANT CONTRIBUTION		
7 DEEP DRIVING FORCES	SOME INFORMATION			IMPORTANT CONTRIBUTION		
8 DRIVE FOR 4-DAY WIND					IMPORTANT CONTRIBUTION	

KEY: SOME INFORMATION; SIGNIFICANT INFORMATION; IMPORTANT CONTRIBUTION; SATISFACTORY ANSWER

QUESTION	GROUND BASED	MARINER 2,5	VENERAS 1-7	PIONEER PROBE	PIONEER ORBITER	MARINER V/M
9 LOSS OF WATER						
10 CO_2 STABILITY						
11 SURFACE COMPOSITION						
12 SEISMIC ACTIVITY						
13 EARTH TIDES						
14 GRAVITATIONAL MOMENTS						
15 EXTENT OF 4-DAY WIND						
16 VERTICAL TEMPERATURE STRUCTURE						


QUESTION
GROUND BASED
MARINER 2,5
VENERAS 1-7
PIONEER PROBE
PIONEER ORBITER
MARINER V/M
17 IONOSPHERIC MOTIONS
18 TURBULENCE
?
19 ION CHEMISTRY
20 EXOSPHERIC TEMPERATURE
21 TOPOGRAPHY
22 MAGNETIC MOMENT
23 BULK ATMOSPHERIC COMPOSITION
24 ANEMOPAUSE

COMPARATIVE MISSION CAPABILITY



Appendix 2

VELOCITIES AND TEMPERATURES EXPECTED IN THE VENUS ATMOSPHERE (R. M. Goody)

MEASUREMENTS

In middle latitudes, at the entry point of Venera 7, the atmosphere is close to adiabatic with a ground temperature approximately 750°K and a pressure of about 90 atmospheres. This close-to-adiabatic state must exist over the whole planet, from pole to equator and day to night, because the surface temperature and the temperature of the cloud tops (approximately 100 mb) do not vary greatly over the planet. The problem of temperature measurement is to detect small departures from adiabaticity and small horizontal temperature variations (along constant pressure surfaces). The most complete analysis of thermal maps is presented in a paper by R. Goody[1].

Equator to pole temperatures are 207°K to 185°K (the absolute calibration of the radiometer may be poor but the temperature difference should be real). We cannot be certain that the cloud tops are at a constant pressure level; however, carbon dioxide line profile measurements have not given any indication to the contrary.

According to the thermal radiometric observations, the day-to-night variation is negative; i.e., night is hotter than day. This difference varies with viewing angle, but can be as much as 6°K for sub-solar to anti-solar point.

Temperatures at the surface of the planet can be measured by microwave interferometry according to a paper by A. C. E. Sinclair[2]. According to this paper, an upper limit of 12°K can be placed on equator-to-pole variations. A significant day-to-night variation of 18.4 ± 9.2°K was reported with the maximum 30°K into the night side from the terminator.

The only data existing with respect to winds is for the 4-day rotation, which now seems to be reasonably well established. Recent interferometric observations (Traub, unpublished) indicate an erratic phenomenon. Nevertheless, there is a tendency towards a zonal circulation (i.e., parallel to latitude circles), at least in the tropical regions, with a velocity of 100 $msec^{-1}$. These observations apply to the 200 mb level and above. The rotation is retrograde and 30 times faster than the apparent motion of the Sun; it is more than 60 times faster than the apparent motion of the stars. There is no evidence whether these 100 $m\,sec^{-1}$ winds exist at levels other than the cloud tops.

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1 Goody, R.: The Structure of the Venus Cloud Veil. Journal of Geophysical Research, 22, 1965, pp. 5471-5481.

2 Sinclair, A.C.E.; et al.: Preliminary Report on Interferometer Observations of Venus at 11.1 cm Wavelength. Radio Science, 5, 1970, pp. 347-354.

THEORY OF THE 4-DAY CIRCULATION

One of the latest papers, which refers to most other theoretical works of importance, is written by P. J. Gierasch.[3] According to this paper and to those of Schubert and Malkus, the circulation is a Halley circulation driven by the moving Sun. Thompson views the motion as a non-linear instability, independent of the rotation of planet. In the latter case, it is difficult to predict what might happen in the deep atmosphere, but in the former case, the circulation will only reach down to the levels at which there is a significant diurnal temperature change.

We know from observation that there is only a small diurnal change of temperature at the cloud tops, and therefore, the 4-day circulation may not penetrate at all below this level.

According to Gierasch's model (which is not universally accepted), the maximum velocity of $100\,m\,sec^{-1}$ occurs at about the 50 mb level and the temperature contrast between day and night sides will be about 5°K.

THE DEEP CIRCULATION: SIMILARITY ARGUMENTS

Because so little is known about the lower atmosphere, it is particularly valuable to have investigations based upon similarity arguments for these deal with imposed constraints, which must be obeyed regardless of details of the mechanism. Two are available.[4,5] Some of the fundamental assumptions differ between these two papers, and the results are therefore debatable. However, despite qualitative differences, they give somewhat similar numerical values for Venus.

Gierasch et al.[5] compare the fundamental radiative time constant for the whole atmosphere (t_s) with the length of the day (t_{day}). The ratio t_s/t_{day} is approximately 10^2 so that the maximum diurnal variation, if the solar energy is shared throughout the atmosphere, is about 2°K. This is the maximum at ground level. At other levels, assuming all the solar radiation is to be deposited above the level concerned, the amplitude increases inversely as the pressure, since $t_s \propto p^{-1}$.

Mean velocities are given by

$$V \sim \frac{\theta_e}{\delta\theta} \frac{R_o}{t_s}$$

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[3] Gierasch, P. J.: The Four-Day Rotation in the Stratosphere of Venus: A Study of Radiative Driving. Icarus, 13, 1970, pp. 25-33.

[4] Golitsyn, G. S.: A Similarity Approach to the General Circulation of Planetary Atmospheres. Icarus, 13, 1970, pp. 1-24.

[5] Gierasch, P. J.; Goody, R.; and Stone, P.: The Energy Balance of Planetary Atmospheres. Geophysical Fluid Dynamics, 1, 1970, pp. 1-18.

where: $\theta_e \sim 230°K$ is the equilibrium temperature; $\delta\theta$ is the temperature contrast, and R_o is the radius of the planet.

The temperature contrast is

$$\frac{\delta\theta}{\theta_e} \sim \frac{t_o}{t_s}^{2/3}$$

where:

$$t_o = \frac{R_o}{\sqrt{R\theta_e}} \sim \frac{R_o}{2 \times 10^4}$$

where: R is the gas constant.

If all of the solar radiation penetrates to the ground,

$$\delta\theta \sim 0.2°K$$

and $V \sim 6 \text{ m sec}^{-1}$

For other conditions,

$$\delta\theta \propto p_o^{-2/3}, \quad V \propto p_o^{-1/3}$$

where: p_o is the limit of penetration of the solar energy.

Golitsyn's study gives, for similar conditions,

$$\delta\theta \sim 1°K$$

$$V \sim 40 \text{ cm sec}^{-1}$$

and

$$\delta\theta \propto p_o^{-1/2}, \quad V \propto p_o^{-1/2}.$$

Gierasch et al. point to a significant difference between the atmosphere below and above the clouds. If the solar radiation is all absorbed in the clouds and if motions distribute the heat, as theory and observation indicate, there may be an upper "stratospheric" regime in which there are virtually no horizontal contrasts and no horizontal drives. The question of the 4-day rotation comes in here and has yet to be treated satisfactorily, but as far as equator-to-pole contrasts are concerned, these authors estimate that a radiatively controlled, "stratospheric" regime could start at about 200 mb pressure; i.e., close to the visible cloud tops.

THE DEEP CIRCULATION: HEURISTIC MODELS

The model of Goody and Robinson[6] was proposed to understand whether the deep atmosphere might be adiabatic without any penetration of solar radiation; i.e., when all the radiation is absorbed at the cloud tops. Stone's paper is an extension of this work.[7] Without any solar penetration only very slow velocities can be expected near to the surface and unmeasurably small temperature contrasts. Since both treatments are two-dimensional, no distinction is made between zonal and meridional contrasts and velocities.

E. de Rivas[11] makes comparison of cloud top conditions for her numerical calculations and the above two papers in Table 7.

Table 7. Velocities and Temperature Contrasts Near the Cloud Tops for Cloud-Top Absorption of Solar Radiation

	Stone	de Rivas	Goody and Robinson
b.l. thickness (km)	1.0	1.0	1.2
horizontal velocity (m sec^{-1})	0.43	5	34
vertical velocity (cm sec^{-1})	0.1	1	0.12
temperature contrast (°K)	6	18	40

THE DEEP CIRCULATION: NUMERICAL MODELS

A fundamental problem with all of these investigations is that they can only integrate for about 100 Earth days. Gierasch, Goody, and Stone stressed, however, that the thermal adjustment time for the lower atmosphere is almost 10^4 Earth days. It is very doubtful whether a useful result can be obtained from a time-marching technique under these circumstances. Papers by S. Hess[8] and by T. Sasamori[9] do not give enough detail to determine temperature contrasts in the lower part of the atmosphere. A Soviet group has used a terrestrial weather prediction scheme to integrate from 90 to 160 Earth days.[10]

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6 Goody, R. M.; and Robinson, A. R.: A Discussion of the Deep Circulation of the Atmosphere of Venus. Ap. J., 146, 1966, pp. 339-355.

7 Stone, P. H.: Some Properties of Hadley Regimes on Rotating and Nonrotating Planets. J. Atmos. Sci., 25, 1968, pp. 644-657.

8 Hess, S.: The Hydrodynamics of Mars and Venus. The Atmospheres of Venus and Mars, Gordon & Breach, New York, 1968.

9 Sasamori, T.: A Numerical Study of the Atmospheric Circulation on Venus. J. Atmos, Sci., 28, 1971, pp. 1045-1057.

10 Chalikov, D. V.; et al.: Numerical Experiments of the General Circulation of Venus' Atmosphere. Tellus, 23, 1971, pp. 483-488.

The Soviet group used a two-layer model, with a base at 80 atmospheres, divided at 40 atmospheres. Their upper-level results are therefore for the 20 atmosphere level while the lower-level is 60 atmospheres.

Two patterns of solar absorption were considered. In one case 80% of the available radiation reaches the ground (greenhouse model). In the other case, the radiation is all absorbed in the upper layer (Goody-Robinson model). The greenhouse model was investigated more extensively. Chalikov et al. conclude that the circulation is symmetric about the equator but not about the pole of rotation or the sun-planet direction and that the highest temperatures lag significantly behind the maximum insolation.

Table 8 gives estimates of the maximum temperature excursions (not to be confused with average day-night temperature differences which are considerably less).

Table 8. Temperature Excursions (°K)

<table>
<tr><th>Model</th><th>Level</th><th>Diurnal</th><th>Latitudinal</th></tr>
<tr><td>Greenhouse</td><td>Surface</td><td>2.5</td><td>1.5</td></tr>
<tr><td></td><td>60 atmos.</td><td>1.4</td><td>0.9</td></tr>
<tr><td></td><td>20 atmos.</td><td>1.2</td><td>0.6</td></tr>
<tr><td>Goody-Robinson</td><td>Surface</td><td colspan="2">1</td></tr>
<tr><td></td><td>60 atmos.
20 atmos.</td><td colspan="2">0.25</td></tr>
</table>

The kinetic energy per unit mass was about the same for both models, corresponding to a horizontal wind of 5.5 m sec^{-1}. Vertical winds have a maximum of a few cm sec^{-1}. Deviations from adiabaticity in the vertical are not given explicitly; however, it is possible to infer that the derivatives must be a few degrees per 100 km or a few parts per thousand of the adiabatic lapse rate.

The de Rivas study is based upon spherical coordinates, but with time-independent solar heating with different geometries.[11] One of her models is for a non-rotating atmosphere with an optical depth for solar radiation of 13.76 and for thermal radiation of 222.0. The vertical mixing coefficient is 10^4 cm^2 sec^{-1}. With these data the solar radiation only heats the top 1/3 of the atmosphere. In this region winds can be 30 m sec^{-1}. In the middle levels winds are 1 cm sec^{-1}

[11] de Rivas, E. K.: Circulation of the Atmosphere of Venus. Ph.D. thesis, Massachusetts Institute of Technology, 1971.

or less and at low levels they are 1 or 2 cm sec^{-1}. Horizontal temperature differences are 3°K near the top, 1°K at 25 km and very small near to the surface. Vertical departures from adiabaticity are 0.3 to 1.5°K km^{-1} in the upper part of the atmosphere.

This model would not by itself maintain a deep adiabatic state, and therefore does not simulate the Venus atmosphere well. A model with $K = 10^3$ cm^2 sec^{-1} gave similar results except that the interior circulation is ten times stronger; i.e., about 10 cm sec^{-1}.

Finally de Rivas considers a model with solar optical depth = 2.3. This allows 6% of the solar radiation to reach the surface and hence gives rise to a substantial greenhouse effect. The high ground temperature, however, requires dynamical heating in addition to radiative and diffusive heating to maintain it. This model has relatively large temperature constrasts even at the ground ($\sim$ 1.5°K), and the vertical stratification is almost 0.2°K km^{-1}. de Rivas does not state the value of the wind velocities near to the ground, but they must be 10 to 100 cm sec^{-1} to create the required advection effects.

CONCLUSIONS

(1) There are a wide variety of theories both for the four-day circulation and for the deep circulation. A few well-conceived measurements are now needed if the subject is to advance further.

(2) The atmosphere divides naturally into two regions at about 100 mb. Above this level diurnal and other short-period effects may be large and dynamical heat transfer relatively small: the dominant winds may be zonal. Below this level the atmosphere has a very long thermal time constant and can be compared to the Earth's oceans as closely as to the Earth's atmosphere. The region above 100 mb is above the clouds. It can be monitored from satellites and from the ground. A device such as IRIS, carried on Mariner 9, would be ideal for investigating this upper region. Balloons would be the best way to measure its winds. Early probes, therefore, should be optimized for the lower atmosphere, which we may define as pressures above 3 atmospheres.

(3) The nature of the circulation depends critically upon penetration of solar energy. The need for simultaneous measurements of cloud scattering properties is clear, and confirms the high priority of a nephelometer on the small probes.

(4) The vertical temperature gradient may depart from the adiabatic lapse rate by as much as 1%. This should be measurable with thermometers having a sensitivity of 0.1°K. Accuracy need not be high and the pressure-time relationship need not be measured directly if height-time is obtained by radio methods.

(5) Horizontal temperature gradients may be small. However, if the ground based interferometric measurements are correct, we can anticipate up to 10°K contrast at the surface. Equator-to-pole contrast may be a few °K. A relative accuracy between probes of 0.5°K is therefore desirable. The absolute accuracy of temperature measurement need not be high: 1% should be sufficient.

(6) Further theoretical studies are needed, but these must be of a climatological nature (i.e., seeking the non-linear steady state) rather than using time marching techniques as has been done in existing studies.

(7) Winds at pressures less than 1 atmosphere may be high, in the range 10 to 100 m sec^{-1}. It seems probable that lower-atmosphere winds are well below 1 m sec^{-1}, but greater than 1 cm sec^{-1}. A precision of 10 cm sec^{-1} in horizontal wind measurements would be of great value. All theoretical treatments agree in predicting small average vertical velocities in the planetary circulation (they have little to say about turbulent eddies). It is not likely that a satisfactory measurement of the steady vertical component can be made from an entry probe.

(8) In accordance with the above, the specifications for the small probes may be set as follows. Similar or better performance should be expected of the large probe. Emphasis is on the region of pressures greater than 1 bar, and especially the lowest 3 scale heights, 0 - 40 km. Performance should be optimized for the 20 - 40 km region.

<u>Specifications for Temperature Measurement</u>

Range	400-750 K (possibly 250-750)
Absolute accuracy	1%
Relative accuracy between probes	0.5K
Equivalent of 1 bit	0.1K
Lag	0.5 sec

<u>Specifications for Pressure Measurement</u>

Range	3-100 bars (possibly 1-100)
Absolute accuracy	5%
Relative accuracy between probes	0.3%
Lag (for 0.3% accuracy)	2.5 sec

Appendix 3

RADIO SCIENCE IN THE CONTEXT OF THE VENUS PROBE MISSION
(G. H. Pettengill)

The ways in which radio measurements relate to the study of the Venus atmosphere differ substantially in the case of a probe mission as compared to an orbiter or fly-by mission. As the probe mission is presently constituted, there will be no occultation opportunities, and thus no way to study the refractive profile of the upper atmosphere and ionosphere in this direct and traditional way. While refractive effects will almost certainly be evident in the radio signals received from the descending probes, these will, in general, be difficult to distinguish from perturbations in the non-ballistic trajectory of the probe as it drifts through the atmosphere. It seems likely that the large-scale homogeneous refractive effects will rather be estimated from the "in situ" measurements of temperature, pressure and composition made by the probe as it descends. The relatively high frequency perturbations in the apparent trajectory may then be assigned to atmospheric (refractive) inhomogeneties along the radio propagation path.

A new method involving doubly differenced, very long baseline interferometry (DLBI) has been proposed as an adjunct to traditional methods of determining trajectory through the use of the observed doppler frequency shift. In this method, the rate-of-change of the phase difference between the signals received at two widely separated sites on Earth is interpreted as caused by motion of the probe in a direction normal to the line-of-sight (and in the plane containing the line-of-sight and sight baseline vector). If this difference is available simultaneously for each of two separate transmitting sources near Venus, a further differencing of these (a so-called symmetric double difference) leads to a determination of their relative lateral motion in which a number of sources of systematic error associated with oscillator and propagation stability have been removed to first order. In this analysis, past experience indicates that the determination of relative probe motions will very possibly be limited primarily by intrinsic signal-to-noise considerations. If this is so, a terrestrial baseline of 8000 km, coupled to a phase measurement accuracy of one electrical degree at S-band, for example, permits detection of a relative velocity at Venus of 10 cm/sec across the line-of-sight after an observing interval of 40 seconds. Systematic errors appear in second order, of course, and place limits to the ultimate accuracy of the DLBI. Nevertheless, the accuracies available are certainly significant to the study of the atmospheric dynamics and appear to be directly competitive with other techniques available such as onboard wind-drift radar.

Since the DLBI technique measures relative velocities, the results are more powerful if at least one source is always visible whose motion is accurately reconstructable from other data. The best source would be the spacecraft "bus", moving in a ballistic trajectory outside the atmosphere of Venus. Since the DLBI technique determines only those components of velocity perpendicular to the line-of-sight, it is important to be able to determine the component of motion along the line-of-sight, from doppler shift, for entries occurring away from the sub-Earth region of the planet where an appreciable part of the horizontal wind velocities show up along the line-of-sight.

In view of the measurement potential of the DLBI, and its intrinsic reliability and relatively low cost (stemming from its location on Earth), we recommend that it be the basic wind measuring system for the Pioneer-Venus Probe Mission. To maximize its effectiveness, we suggest the following mission requirements:

(1) That a transponder be placed on the large probe to ensure the maximum possible accuracy in the determination of its descent trajectory.

(2) That the entry of the bus into (and its subsequent destruction in) the atmosphere of Venus be delayed by at least one hour relative to the mean entry time of the probes. This can be accomplished by use of its attached rocket motor following release of the probes. Use of the bus transponder and, if possible, also its ranging system should not be precluded during this terminal phase.

(3) That a transmission oscillator be used which will permit reconstruction of the frequency emitted by each small probe to an accuracy of one part in 10^9. If this is not possible, a useful wind measurement capability, albeit at a degraded level, will still occur if the emitted frequency reconstructability is adequate to permit observing horizontal winds to an accuracy of 1 m/sec. (The corresponding frequency stability required has not yet been established.)

(4) That the downlink frequencies of the various probes and the bus be chosen as close together as practicable to minimize uncompensated dispersive effects. These effects may degrade measurement accuracies for downlink frequency separations greater than about 100 KHz.

Appendix 4

ATMOSPHERIC CHEMISTRY

MASS SPECTROMETRY (U. von Zahn, D. Hunten, J. Lewis)

Measurements of composition at various heights in the Venus atmosphere can contribute to a large number of scientific objectives:

(1) Information can be provided on the origin and evolution of the planetary system, and particularly of Venus. The sensitive measurements are of some isotopes of the rare gases, and of nitrogen and other volatiles.

(2) The heat balance of Venus is related to the opacity of clouds and of possible minor constituents; latent heat of condensation may also be important. The presence and distribution of these substances should therefore be measured.

(3) Though CO_2 is probably at least 95% of the atmosphere, the remaining 0-5% needs to be identified.

(4) The nature of the upper atmosphere is determined by a competition between mechanical mixing and molecular diffusion, which can be represented by the height of a "turbopause". This height can be measured by comparing the relative abundances of suitable gases in the upper atmosphere (bus measurement) and lower atmosphere (probe measurement). Comparison of bus and orbiter measurements can give information on variability of the upper atmosphere. The best candidate gases are He, N_2, and Ar.

(5) Upper-atmospheric temperature profiles can be determined from the scale heights of individual gases.

(6) A major problem in the upper atmosphere is the unexpected stability of CO_2 (or lack of its photolysis products, CO and O). This problem can be understood, or at least described, by measurements of these gases.

(7) Ion-density profiles are far more informative about upper-atmospheric processes than electron-density profiles. They not only tell us about the ionosphere; they also permit inferences about the neutral atmosphere from our knowledge of reaction rates. Ion measurements may give us the deuterium/hydrogen ratio much better than neutral measurements, as on Earth.

(8) The possible sweeping away of light constituents by the solar wind can be studied, particularly by ion measurements at the interface of solar wind and ionosphere.

For design purposes, the following estimates of possible abundances may be useful. In the inert category fall the noble gases and nitrogen. Mainly due to the results of the Venera probes, it is generally accepted that 5% is the upper limit for the abundance of N_2 in the Venus atmosphere. It is, however, important to note that recent models on planetary evolution predict an abundance orders of magnitude smaller than the above value. The abundances of noble gases of radiogenic origin have been estimated[1] to be: 100 ppm for ^{40}Ar and 200 ppm for ^{4}He. Predictions about the abundances of primordial gases such as ^{3}He, the Ne isotopes, ^{36}Ar, ^{38}Ar, and heavier noble gases are almost impossible to make. The best candidates for a mass spectrometric measurement appear to be ^{20}Ne and ^{36}Ar. Although it will be very desirable to measure additional isotopes of Ne, Ar, Kr, and Xe, it is felt that a good measurement of ^{20}Ne and ^{36}Ar will answer some basic questions about the origin of the Venus atmosphere.

Estimates for the abundances of gases in the deep atmosphere, which may form clouds, or contribute to cloud formation, in the middle atmosphere, range as follows:

H_2O	< 0.7%, but probably much lower
HBr, HI	< 1000 ppm
HCl	1 ppm
HF	0.01 ppm
Hg	10-1000 ppm
HgI_2	10 ppm
HgBr	10 ppm
COS	1 ppm

Numerous other gases are likely contributors to cloud formation, like HgS, Hg_2Cl_2, CO_2, Sb_2S_3, etc. Thermodynamic and spectroscopic data do not support the contention that $FeCl_2$ vapor is important anywhere in the atmosphere.[2,3]

In addition to gases already listed above which are reactive but probably not cloud-forming, the following should be included:

CO_2	> 95%
CO	50 ppm,

as well as H_2S, SO_2 and additional compounds of As, Sb.

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1 Knudsen, W. C.; and Anderson, A. A.: Estimate of Radiogenic He^4 and Ar^{40} Concentration in the Cytherean Atmosphere. Journal of Geophysical Research, 74, 1969, pp. 5629.

2 Lewis, J. S.: Geochemistry of the Volatile Elements on Venus. Icarus, 11, 1969, pp. 367.

3 Hunten, D. M.: Composition and Structure of Planetary Atmospheres. Space Science Reviews, 12, 1971, pp. 539.

Of the known gases, the main contributions to the IR opacity of the lower Venus atmosphere stem from CO_2 and H_2O. The observed amounts of CO_2 and H_2O, however, do not yield a high enough IR opacity to allow a satisfactory explanation of the observed blanketing. The difference is usually assumed to be due to clouds, but in addition the mass spectrometer will search for additional IR active gases with abundances higher than 10 ppm of CO_2. Likely candidate gases are HBr, HI, and, depending on their actual abundance, COS, H_2S, etc.

ORIGIN AND CHEMISTRY OF THE VENUS ATMOSPHERE (J. S. Lewis)

The general decrease of densities of solid solar system bodies with increasing heliocentric distance suggests a dependence of accretion temperature on distance, with bodies close to the sun formed at rather high temperatures. The temperature of formation influences two observable properties of the planets; the bulk density and the degree of retention of volatiles. Calculations on the chemistry of solar material over wide ranges of temperature and pressure give detailed predictions of the bulk condensate density and of water and sulfur content which can be directly compared to observation[4]. The volatile content of the earth is compatible with either an equilibrium origin at approximately 600°K or with origin at a higher temperature with addition of approximately 1% by mass of volatile-rich material such as type I carbonaceous chondrites.

A model for the bulk composition and volatile content of Venus based on the equilibrium model suggests essentially zero sulfur content and zero water content, with a relatively FeO-free mantle and a solid Fe-Ni core. The observed H_2O content of the Venus atmosphere accounts for $\leq 10^{-9}$ of the mass of Venus, while no gaseous sulfur compounds (COS, SO_2, H_2S, etc.) have ever been detected by Earth-based spectroscopic observations. It is not clear whether this amount of water (10^4 times less than on Earth) requires a special explanation, since a single, large (20 km radius) comet head could supply this amount.

Any chemical equilibrium approach to explaning the observed composition of the atmosphere in terms of chemical reactions between atmospheric gases and surface minerals shows that sulfur-bearing surface rocks would always give rise to observable amounts of sulfur gases in the lower atmosphere[5]. The observational failure to detect these gases by IR spectroscopy can be interpreted in at least three ways: (1) Venus contains no sulfur; (2) Venus has differentiated in such a way as to "bury" all the sulfur; or (3) sulfur is present in the lower atmosphere, but precipitates as cloud-forming compounds below spectroscopically accessible levels.

Any "in situ" mass spectrometric analysis must be directed to answering three questions. First, the composition of the chemically reactive portion of the atmosphere (which is in chemical equilibrium with the surface of the planet) must be determined. Second, the abundances of gases containing elements which may form clouds must be measured deep in the atmosphere ($T = 650 \pm 100$°K) below

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4 Lewis, J. S.; Earth Planetary Science Letter, in press, 1972.

5 Lewis, J. S.: Venus Atmospheric and Lithospheric Composition. Earth Planetary Science Letter, 10, 1970, pp. 73-80.

the bases of most plausible cloud layers. The deepest possible penetration into the lower atmosphere is desirable ($T \geq 700°K$). Third, chemically-inert gases diagnostic of the amount of primordial volatile material retained by Venus should be analyzed in isolation in a chemically cleaned sample.

The most important chemically reactive gases to be measured are CO_2, H_2O, CO, HCl, HBr, HI, HF, COS, H_2S, SO_2, and compounds of As, Sb, and Hg. Among the "inert" gases, N_2, ^{40}Ar, ^{4}He, and primordial gases such as ^{3}He, ^{20}Ne, ^{22}Ne, ^{36}Ar, ^{38}Ar, Kr and Xe, would all be useful. Among these the fundamental importance of sulfur, nitrogen, and light rare gases commend them especially to our attention.

If it is assumed that several mass-spectrometer analyses at widely separated altitudes and detailed nephelometer data will be available, then there is no significant advantage to attempting direct analyses of cloud particles. Pressure and temperature profiles combined with available thermochemical data would permit a straightforward calculation of the altitudes at which various components of the lower atmosphere would saturate.

The dynamic range required of the mass spectrometer is dictated by the expected abundances of Br, I, S, Hg, As, and Sb in the lower atmosphere. Cloud-forming condensates with abundances less than 10^{-6} of CO_2 will be unimportant, while a terrestrial analogy suggests upper limits of approximately 10^{-2}, 10^{-3}, 10^{-4}, 10^{-3}, 10^{-3}, and 10^{-4} for the respective mole fractions of the elements. A dynamic range better than $10^4:1$ is required, and $10^5:1$ is a reasonable minimum target.

Appendix 5

MAGNETIC MEASUREMENTS (PIONEER-VENUS)
(C. T. Russell)

Magnetic field measurements can lead to a better understanding of the Venus interior, surface, and ionosphere and also provide information on the solar wind interaction with the Venus ionosphere and on processes within the solar wind itself. The measurement of an overall planetary magnetic field similar to the Earth although necessarily much smaller in magnitude would indicate the existence of a planetary dynamo. The presence of surface magnetism, similar to the irregular lunar magnetic field, in addition to providing information on the magnetic properties of the Venus surface rocks, would be evidence for a primordial planetary magnetic field.

The vertical profile of the ionospheric magnetic field provides a measure of the ionospheric current system, which can be compared with the various ionospheric models. For example, these current systems may depend on the electric field of the solar wind, or the ionosphere may be decoupled from this electric field. A further investigation of this coupling is provided by measurements of the magnetic field at the solar wind-ionospheric interface. A component of the magnetic field normal to this interface indicates coupling.

Outside the solar wind-ionosphere interface, the loss of neutral hydrogen from the upper atmosphere and the subsequent charge exchange and acceleration of the resulting slow ion by the solar wind electric field will "unfreeze" the magnetic field from the solar wind flow. A determination of the distortion of the field in this region will provide a measure of the importance of the mass loss process.

Away from the planet, the magnetic field measurements in conjunction with the solar wind measurements can use the dual launch nature of the probe mission to measure the time evolution of the interplanetary structure.

Although this is to a large extent an exploratory mission, we can make some estimates as to the size of fields we expect to measure and the resolution with which we need to make these measurements. This is necessary for both spacecraft design and to set the magnetic constraints for spacecraft systems.

If we scale the planetary field of the Earth to that of Venus by the ratio of their rotation rates we obtain a field of the order of 100γ. Direct observation indicates that the planetary field may be even lower. Models of the ionospheric magnetic field give field strengths from 10γ to 100γ. The latter field strength represents a field that would stand off the solar wind. Thus, the minimum field strength in the vicinity of the small probes should be of the order of 10γ. The field strengths found thus far on the surface of the moon range from 0 to 300γ. It is expected that this is a reasonable estimate for Venus also, and the small probes should be designed accordingly.

Loss of accuracy in measuring small field changes can occur if the background spacecraft field strength greatly exceeds the field being measured. This requires the small probe background field to be less than about 100γ. Owing to the simplicity of the small probe, it is believed that this limit can be achieved at acceptable expense both parallel to and perpendicular to the spin axis.

To remove the contribution of the spacecraft field, this must remain stable. It is intended to calibrate the small probe field so that it can be predicted to less than 10γ.

The bus magnetometer finds itself in a different environment. The ionospheric fields have a maximum strength of the order of 100γ. The fields in the interplanetary medium are of the order of 5γ. The determination of boundary normals requires differential measurements to the order of γ/4. Techniques, however, exist for measuring the spacecraft field using the characteristics of the interplanetary medium. Thus, if the spacecraft field is small (of the order of 5γ) and stable, it can be removed. If the spacecraft field is much larger than the interplanetary field, then the determination of the spacecraft field becomes insufficient for reducing the interplanetary data to absolute fields. If the spacecraft field is not constant for long periods, of the order of days, this technique also becomes less accurate.

Appendix 6

MODEL ATMOSPHERES

The SSG has addressed the question of model atmospheres for design of the Pioneer-Venus probes and recommends the adoption of the atmospheres described in NASA SP 8001[1]. The document carefully reviews and evaluates the current literature on the atmosphere of Venus, with emphasis on the spacecraft data of Mariner V and the Venera probes. The model atmospheres described are consistent with those data, as well as with the bulk of recent Earth-based data on planetary radius, terrain elevations, cloud particle sizes, and index of refraction.

The six models given in the document exhibit only minor differences below 120 km, but differ significantly in modeling of the turbopause and exospheric regions, the latter depending on the level of solar activity and dayside - nightside differences in the ionosphere. These upper levels of the atmosphere are important to the design of the bus and orbiter and their experiments, but are less important for the design of the probes. For the probes, these models are effectively one, having most probable surface pressures up to 97 atmospheres and temperatures of 773°K. It is our recommendation that a probable radius of the planet (6050 km based on existing data) be chosen as the design point.

We have emphasized in Chapter 2 of this report that the probe mission is an atmospheric mission requiring only penetration near to the mean planetary radius. If the probes survive to 97 atmospheres and 773°K, the mission would be considered completely successful. Table 9 lists the data for the recommended model atmosphere.

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1 NASA Space Vehicle Design Criteria (Environmental) Models of the Venus Atmosphere. NASA SP 8001, 1972.

Table 9. Venus Model Atmosphere (Most Probable Density and Mean Solar Activity)

HEIGHT (KM)	TEMP (K)	PRESSURE (MILLIBAR)	DENSITY (GM/CC)	SPEED OF SOUND (M/SEC)	MOLECULAR WEIGHT	DENS. SCALE (KM)	NUMBER DENSITY (PER CC)	MEAN FREE PATH (M)	VIS-COSITY (**)
-4	798.1	1.20E+05	7.89E-02	426.	43.531	20.52	1.09E+21	1.33E-09	3.33E-05
* 0	767.5	9.49E+04	6.47E-02	418.	43.531	19.79	8.95E+20	1.62E-09	3.24E-05
4	736.5	7.41E+04	5.27E-02	410.	43.531	19.06	7.29E+20	1.89E-09	3.15E-05
8	705.2	5.73E+04	4.25E-02	402.	43.531	18.32	5.88E+20	2.46E-09	3.06E-05
12	673.4	4.38E+04	3.40E-02	393.	43.531	17.57	4.71E+20	3.07E-09	2.96E-05
16	641.2	3.30E+04	2.70E-02	384.	43.531	16.81	3.73E+20	3.88E-09	2.85E-05
20	608.5	2.46E+04	2.11E-02	375.	43.531	16.03	2.93E+20	4.95E-09	2.74E-05
24	575.3	1.80E+04	1.64E-02	365.	43.531	15.24	2.27E+20	6.395-09	2.62E-05
28	541.4	1.29E+04	1.25E-02	355.	43.531	14.43	1.73E+20	8.36E-09	2.51E-05
32	506.8	9.10E+03	9.40E-03	345.	43.531	13.59	1.30E+20	1.11E-08	2.39E-05
36	471.4	6.25E+03	6.94E-03	334.	43.531	12.74	9.61E+19	1.51E-08	2.25E-05
40	433.0	4.16E+03	5.03E-03	321.	43.531	11.82	6.97E+19	2.08E-08	2.09E-05
44	397.6	2.67E+03	3.52E-03	308.	43.531	10.51	4.87E+19	2.97E-08	1.95E-05
48	371.4	1.66E+03	2.34E-03	299.	43.531	9.19	3.23E+19	4.47E-08	1.82E-05
52	336.8	9.91E+02	1.54E-03	286.	43.531	9.36	2.13E+19	6.79E-08	1.65E-05
56	299.6	5.57E+02	9.74E-04	271.	43.531	7.99	1.35E+19	1.07E-07	1.49E-05
60	267.6	2.93E+02	5.72E-04	258.	43.531	7.12	7.92E+18	1.83E-07	1.33E-05
64	246.2	1.44E+02	3.06E-04	249.	43.531	6.13	4.24E+18	3.42E-07	1.23E-05
68	231.9	6.71E+01	1.51E-04	242.	43.531	5.47	2.10E+18	6.91E-07	1.16E-05

* 0 km height is 6050 km radial distance from planetary center.

** Newton seconds per $(\text{meter})^2$

Table 9. Venus Model Atmosphere (Most Probable Density and Mean Solar Activity) (Contd)

HEIGHT (KM)	TEMP (K)	PRESSURE (MILLIBAR)	DENSITY (GM/CC)	SPEED OF SOUND (M/SEC)	MOLECULAR WEIGHT	DENS. SCALE (KM)	NUMBER DENSITY (PER CC)	MEAN FREE PATH (M)	VIS-COSITY (**)
72	217.0	2.99E+01	7.22E-05	235.	43.531	5.30	9.99E+17	1.45E-06	1.10E-05
76	200.4	1.25E+01	3.27E-05	227.	43.531	4.76	4.53E+17	3.20E-06	1.03E-05
80	187.9	4.92E+00	1.37E-05	211.	43.531	4.46	1.90E+17	7.63E-06	.94E-05
84	180.1	1.84E+00	5.35E-06	203.	43.531	4.16	7.40E+16	1.95E-05	.89E-05
88	175.2	6.65E-01	1.99E-06	199.	43.531	3.97	2.75E+16	5.27E-05	.86E-05
92	171.4	2.35E-01	7.16E-07	195.	43.531	3.88	9.91E+15	1.46E-04	.83E-05
96	168.3	8.11E-02	2.52E-07	193.	43.531	3.77	3.49E+15	4.15E-04	.81E-05
106	165.4	5.41E-03	1.71E-08	191.	43.531	3.57	2.37E+14	6.11E-03	.80E-05
116	183.1	4.02E-04	1.15E-09	206.	43.531	3.67	1.59E+13	9.10E-02	.91E-05
126	211.9	4.41E-05	1.09E-10	233.	43.531	4.70	1.51E+12	9.60E-01	1.08E-05
136	246.4	5.98E-06	1.27E-11	249.	43.531	4.94	1.76E+11	8.24E+00	1.23E-05
146	334.3	1.26E-06	1.97E-12	290.	42.429	6.08	2.73E+10	5.32E+01	1.64E-05
156	452.8	4.22E-07	4.63E-13	337.	41.321	8.14	6.75E+09	2.16E+02	2.17E-05
166	555.6	1.87E-07	1.62E-13	376.	39.998	10.84	2.44E+09	5.97E+02	2.55E-05
176	521.3	9.58E-08	7.13E-14	404.	38.435	13.37	1.12E+09	1.30E+03	2.78E-05
186	661.5	5.33E-08	3.54E-14	427.	38.594	15.16	5.83E+08	2.50E+03	2.91E-05
196	684.9	3.14E-08	1.90E-14	447.	34.486	16.88	3.32E+08	4.38E+03	2.99E-05
206	697.1	1.94E-08	1.08E-14	466.	32.154	18.24	2.01E+08	7.22E+03	3.03E-05
216	703.6	1.25E-08	6.34E-15	487.	29.693	19.62	1.29E+08	1.13E+04	3.05E-05

** Newton seconds per $(\text{meter})^2$

Table 9. Venus Model Atmosphere (Most Probable Density and Mean Solar Activity) (Contd)

HEIGHT (KM)	TEMP (K)	PRESSURE (MILLIBAR)	DENSITY (GM/CC)	SPEED OF SOUND (M/SEC)	MOLECULAR WEIGHT	DENS. SCALE (KM)	NUMBER DENSITY (PER CC)	MEAN FREE PATH (M)	VIS-COSITY (**)
226	706.9	8.37E-09	3.88E-15	510.	27.226	21.10	8.57E+07	1.70E+04	3.06E-05
236	708.5	5.81E-09	2.45E-15	534.	24.877	22.77	5.94E+07	2.45E+04	3.07E-05
246	709.2	4.17E-09	1.61E-15	559.	22.743	24.71	4.26E+07	3.41E+04	3.07E-05
256	709.4	3.08E-09	1.09E-15	584.	20.876	26.89	3.15E+07	4.62E+04	3.07E-05
266	709.4	2.34E-09	7.64E-16	607.	19.283	29.23	2.39E+07	6.10E+04	3.07E-05
276	709.4	1.81E-09	5.50E-16	630.	17.942	31.69	1.85E+07	7.88E+04	3.07E-05
286	709.4	1.42E-09	4.06E-16	650.	16.812	34.18	1.45E+07	1.00E+05	3.07E-05
296	709.4	1.14E-09	3.06E-16	670.	15.848	36.59	1.16E+07	1.25E+05	3.07E-05
306	709.4	9.23E-10	2.35E-16	688.	15.008	38.87	9.43E+06	1.54E+05	3.07E-05
316	709.5	7.57E-10	1.83E-16	706.	14.257	40.99	7.72E+06	1.88E+05	3.07E-05
326	709.5	6.26E-10	1.44E-16	724.	13.569	42.96	6.40E+06	2.28E+05	3.07E-05
336	709.5	5.24E-10	1.15E-16	742.	12.922	44.81	5.35E+06	2.72E+05	3.07E-05
346	709.5	4.42E-10	9.21E-17	760.	12.304	46.56	4.51E+06	3.23E+05	3.07E-05

** Newton seconds per $(\text{meter})^2$

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