JPL PUBLICATION 77-51, VOLUME III

# Report of the Terrestrial Bodies Science Working Group

## Volume III. Venus

(NASA-CR-155187) REPORT OF THE TERRESTRIAL BODIES SCIENCE WORKING GROUP. VOLUME 3: VENUS (Jet Propulsion Lab.) 33 p HC A03/MF A01 CSCL 03B

N77-34076

Unclas
G3/91 50479

National Aeronautics and
Space Administration

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OVERLEAF: Venus—Hidden by a Veil of Clouds

Venus, most like the Earth in size but possessing a thick carbon dioxide atmosphere spiked with exotic spices of acid, has revealed to Earth-based radar observers tantalizing glimpses of craters, mountains, canyons and volcanoes. Diverse atmospheric phenomena, combined with evidence of surface geology like that of Earth, make Venus an exciting prospect for future exploration.
(Mariner 10 photomosaic of Venus taken in ultraviolet light; JPL photograph P-14400)

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September 15, 1977

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# PREFACE

This volume is one of a nine-volume series documenting the work of the NASA-sponsored Terrestrial Bodies Science Working Group in developing plans for the exploration of Mercury, Venus, the Moon, Mars, asteroids, Galilean satellites, and comets during the period 1980-1990. Principal recommendations and conclusions are contained in Volume I (Executive Summary); reports and working papers of the study subgroups are presented in Volumes II-IX.

This volume is the report of the Venus subgroup, whose members and contributors are W. M. Kaula (chairman), M. C. Malin, H. Masursky, G. Pettengill, R. Prinn, and R. E. Young.

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# SECTION I

# SCIENCE OBJECTIVES

## A. INTRODUCTION

Venus is the terrestrial planet which most resembles the Earth in bulk properties: mass, mean density, and distance from the Sun. However, Venus is still the most mysterious of the terrestrial planets because so much of it is concealed by the massive, opaque atmosphere. The most marked known differences of Venus from the Earth are the very slow retrograde rotation ($243^d$ period), the absence of a satellite, the massive atmosphere of $CO_2$ (90 bars surface pressure), the high surface temperature of 740 K, and the absence of a significant magnetic field. The mass of $CO_2$ is about equal to that in the Earth's oceans and carbonate rocks. However, $H_2O$ is almost entirely absent. It is probable that the reduced iron required by the mean density is in a core, since the 1.5-km offset between center-of-mass and center-of-figure plus Venera spacecraft gamma ray measurements indicate that Venus has been hot enough to differentiate an appreciable crust. Despite this probable existence of a core, Venus appears to have only a slight magnetic field, with a dipole intensity at the surface of about $30\gamma$. Consequently, solar wind interaction with the planet is likely to be a direct balancing of the wind dynamic pressure against the thermal ionospheric static plasma pressure and may play an important role in determining the properties of the upper atmosphere. The Sun also affects Venus through photochemical processes which should be important down to at least cloud top level, about 60 km altitude. However, the predominance of $CO_2$ is remarkable; either the dissociation products CO, O and $O_2$ are rapidly circulated downward and recombined thermochemically, or there are further in situ reactions. The principal observed atmospheric constituents, aside from $CO_2$ are CO ($\sim$0.01%) and $H_2O$ ($\leq$0.01%). The upper limit of the $N_2$ content is 2%. The visible clouds are believed to be mainly $H_2SO_4$, and probably extend down to 50 km altitude. The most prominent features of the upper atmospheric circulation are mean zonal winds on the order of 100 m/sec and horizontal temperature contrasts at cloud level of about 10 K.

Venus is of unique interest because of its similarity to Earth in bulk properties. The marked present differences from Earth may have been the consequence of marginal differences in initial conditions and hence better understanding of Venusian evolution would contribute greatly to understanding the Earth's evolution.

Venus will soon be subject to reconnaissance exploration by the Pioneer Venus spacecraft. This project, which will combine an orbiter and five probes (one a bus for the others), is primarily designed for atmospheric exploration. It is expected (1) to determine detailed information about cloud structure and composition, circulation above the clouds (the four-day wind), and ionospheric structure, and (2) to study lower atmosphere composition and structure, atmospheric dynamics, the magnetic and gravitational fields, and the broad variations in topography.

## B. ORIGIN: CORE FORMATION AND EVOLUTION

In virtually all models of solar system origin, the formation of Venus is similar to the Earth's in all respects save that its constituents are more refractory, because it formed closer to the Sun. The principal difference in composition from the Earth is generally thought to be a large deficiency in sulfur, which is believed to condense from the nebula at about 700 K. The somewhat lower mean density of Venus (relative to the Earth) would be a consequence of this deficiency. An alternative possibility is a higher oxidation level in Venus; the $CO_2$ atmosphere indicates that it may have also acquired appreciable $H_2O$. A more puzzling difference of Venus is the high potassium-to-thorium (K:Th) ratio measured by the Venera 8 and 9 landers: 6000, compared to 3000 on Earth. Potassium is relatively volatile, but is expected to be condensed at both the Earth and Venus. One hypothesis is that, at higher pressures, potassium may have an affinity for iron sulfide, and thus go to the core in the Earth, but not in a Venus lacking sulfur.

While it is likely that Venus is crudely more refractory than the Earth, it is desirable to determine better its bulk constitution in order to place tighter constraints on temporal variation of solar nebula conditions and on the shifting about in the nebula of protoplanetary material. The crust of Venus is probably as unrepresentative of the whole planet as is the crust of the Earth. To constrain models of its internal composition, seismometry on Venus's surface is desirable. The level of seismicity would determine how long a seismometer must be maintained to obtain this information, as well as being of interest for its own sake as an indicator of tectonic activity. Also wanted as indicators of the circumstances of planetary origin are the relative abundances of trace elements of similar chemistry. For example, the ratios of the inert gases He, Ne, A, Kr, and Xe would indicate whether the proto-Venus material lost volatiles while still in the form of rather small bodies (as appears to be the case for the Earth) or at a later stage of evolution.

A measurement pertaining to the deep interior of Venus, and thence to its early evolution, would be magnetometry at a variety of locations close to the planet. The upper limit of 30$\gamma$ on surface field intensity inferred from existing magnetometry assumed the magnetic field to be purely a dipole. The data are uneven enough, however, that shorter wavelength intensities of 100$\gamma$ or more could exist. For a slowly rotating planet like Venus, such intensities could allow an active hydromagnetic dynamo. Magnetometry might thus constrain energy sources and convective mechanisms for dynamo models.

Also of possible relevance to the behavior of Venus's core and its interaction with the mantle is Venus's slow retrograde spin. The achievement and stabilization of this state may have required appreciable internal dissipation, such as would occur at the interface between a fluid core and a solid mantle. Internal dissipation would also be required to enable capture of Venus's spin into a synchronization with the Earth, as has been suggested and is still remotely possible. Such a synchronization further requires an appreciable difference of moments of inertia for stability. Hence more accurate measurement of the gravity field is desirable to determine this parameter.

The retrograde spin may be related to Venus's lack of a satellite. If Venus were despun by an external mechanism, such as solar tides or planetesimal impact, then tidal friction would cause any satellite to spiral into the planet. An alternative hypothesis is that Venus had a spin rate like the Earth and a satellite of comparable size to the Earth's, but of moderately larger orbital eccentricity: large enough that the effect of tidal friction in Venus increased the eccentricity until the satellite orbit became hyperbolic relative to Venus. The most likely fate of such a satellite would have been to come back into Venus, with fair probability of knocking the spin retrograde. Evidences pertaining to these problems would be indicators of Venus's dissipatory properties or gross asymmetry attributable to satellite impact.

## C. EVOLUTION OF THE MANTLE AND CRUST

The refractory natures of uranium and thorium, together with the high potassium-to-thorium ratio, indicate that Venus probably has at least the same density of heat sources as does the Earth. This circumstance, together with the similar size, should lead to a similar thermal and tectonic evolution. The higher surface temperature of Venus would merely lead to a shallower depth at which convective heat transport becomes dominant over conductive transport. Evidence of such a thinner lithosphere would come from the mapping by imaging radar and altimetry of tectonic features which are of smaller length scale than on the Earth.

Of more fundamental significance may be a lack of water in Venus. A few tenths of a percent of water can change the melting point of rocks by 400 K. Extreme dryness in Venus would almost entirely compensate for the high surface temperature in determining lithospheric thickness. Higher internal temperatures would be necessary to lower viscosity sufficiently to attain a steady-state convective system (one in which, on the average, heat is removed at the same rate at which it is generated). Water may also be important to long-term compositional evolution: its presence may have a great influence on the extent to which crustal material can be recycled, as appears to be characteristic of most of the Earth's history. It is possible that Venus is more like the Moon in that its dryness results in all differentiated rocks remaining within the crust, without appreciable recycling. Compositional evolution has major effects on planetary thermal evolution by influencing the distribution of heat sources: uranium, thorium, and potassium are all large-ion lithophiles which tend to collect in the crust, so that the inevitable consequence of nearly complete compositional stratification is thermal quiescence. Terrestrial planet interiors can be said to differ mainly in the rate and manner by which they approach this state.

Somewhat difficult to reconcile with a low degree of recycling are the high K, U, Th crustal abundances indicated by the Venera 8 gamma-ray experiment. This high level is found on Earth only in rocks which are products of repeated differentiation. It is desirable to obtain independent verification of these abundances. Measurements of the major compositional constituents by neutron activation or other techniques at as varied a sampling of sites as possible are also important to understand the extent and nature of crustal differentiation, recycling, and refinement.

Orbital geophysical measurements pertaining to the nature of the tectonic regime and thermal evolution of Venus include gravity variations by satellite orbit perturbations, radar altimetry, and radar imaging. The gravimetry and altimetry will give estimates of the degree to which isostasy prevails, and thence of the level of broad-scale tectonic activity as well as the minimum mean crustal thickness. It is of major interest to determine whether there is an extended network of up- and down-wellings, like the Earth's rift and subduction zones, or only occasional puncturings of the lithosphere by volcanism together with passive rifting due to thermal expansion, as on Mars. Widespread mapping with higher-resolution images is required to determine the nature and extent of volcanism and other features indicative of internal magmatic activity. Images are also necessary to select the optimal sites to answer key questions by surface landers carrying compositional experiments.

Finally, it is necessary to have geophysical measurements over a sufficient duration to determine internal structure and thermal state. If there is a moderate level of seismicity, then internal layering from either compositional or thermal effects can be determined from the velocity and amplitude variations of seismic wave propagation. The locations of seismicity are also of value in determining the nature of tectonic activity. Heat flow measurements at a variety of sites are also needed to determine the density of heat sources. Surface magnetometry, in conjunction with orbital data, could be used to infer the internal electrical conductivity, and thence temperature. These measurements, combined with the seismology, will enable extrapolation from the compositional measurements mentioned above to determine Venus's stage in the upward differentiation of heat sources and to describe the tectonic mechanisms and degree of recycling involved.

## D. EXOGENIC EFFECTS ON SURFACE STRUCTURE

All bodies in the solar system have been subjected to intensive meteoritic bombardment during their lifetime, and Venus is no exception. For the airless bodies such as Mercury and the Moon, the record of these impacts is almost perfectly preserved, save for tectonic and erosive processes of relatively modest proportions. For those terrestrial bodies with non-negligible atmospheres (Venus, Earth and Mars), further modification of the surface record of these impacts has been significant first through atmospheric filtering of the incoming meteorites, and second by extensive atmosphere-related erosion and sedimentation.

The filtering effect of an atmosphere both reduces meteorite velocity by aerodynamic drag and meteorite mass by ablation. Both processes are far more severe in reducing the kinetic energy of small meteorites than of large ones, and thus tend to attenuate greatly the population of small impact craters while affecting large ones hardly at all. The chief effect is to reduce in abundance those craters 10 km in diameter and smaller. Thus, craters 30 km or larger should have been created as frequently on Venus as on Mercury.

In addition, the gravity of the target planet affects the detailed morphology of an impact crater. On Venus, the distribution of secondary craters is further confined by atmospheric drag.

Given these characteristics of impact crater production, what sort of erosive modification should we expect? Liquid water is unlikely to have played any important role unless the early phases of the planet's evolution were vastly different from the situation we see today. It is unlikely that chemical weathering would be effective on any scale larger than a few centimeters. Eolian erosion is probably most important. The surface winds on Venus blow at about 1 m/sec. Because of the high atmospheric density at the surface (0.06 gm $cm^{-3}$), this is not a negligible velocity: the wind pressure would approximate that of a 17-mph breeze on Earth. If particles were entrained in the lower atmosphere, they might well have significant erosive (sandblasting) effect over eons of time. From very limited data (Venera 9 and 10 images), there do not appear to be many particles so entrained, and a detailed estimate of eolian effects is difficult.

Although only a few percent of the Venus surface has been observed by radar to the necessary resolution, several crater-like features ranging from 100 to over 1000 km in diameter have already been seen. If in fact impact craters, these features indicate that the cratering does not approach the scale of Mars, but exceeds that of Earth.

Coverage at a few km resolution of a far greater portion of Venus than is now available is needed to establish the precise crater distributions at several widely separated locations and to determine the extent of the erosive processes acting on the surface.

## E. CHEMISTRY, PHYSICS, AND CHEMICAL EVOLUTION OF THE ATMOSPHERE

The 1978 Pioneer Venus Multiprobe and Orbiter missions will provide new and significant information concerning the Venusian atmosphere. However, there are major questions which cannot be answered by the Pioneer data, because of limited payload, and new questions arise which we cannot predict at this time. With this caution, what appear to be the major problems for resolution in the post-Pioneer era follow:

### 1. Ionosphere, Exosphere, and Bow Shock Region

This region will be very well served by the various Pioneer Orbiter and Multiprobe bus experiments, but a few gaps will remain. A complete map of the bowshock and ionopause boundaries will not have been produced, basic knowledge of low-energy particle fluxes will be absent, and finally, observations of Venus during a sunspot minimum will be needed to complement the Pioneer Venus sunspot maximum observations.

## 2. Neutral Atmosphere

The extremely important region of the atmosphere between the 65- and 135-km altitudes will receive little attention during the Pioneer Mission. This is the photochemically active region of the atmosphere and basic questions concerning atmospheric composition, vertical mixing rates, stability and evolution cannot be answered until we fully understand the chemistry and physics of this region. Important chemically active species to measure in a post-Pioneer mission include $H_2$, $H_2O$, $HC\ell$, COS, $SO_2$, $H_2S$, $SO_3$, $H_2O_2$, $O_2$, $O_3$, $NO_2$, $HNO_3$, and if possible the short-lived species $C\ell$, $C\ell O$, $OC\ell O$, $C\ell OO$, OH, and $HO_2$. Measurements of a light inert gas such as He would help define the turbopause. In situ mass spectrometer measurements would be ideal for the more stable species but there are problems with high-altitude deceleration of entry probes to enable adequate sampling. Techniques to detect some of the short-lived species are presently being developed for use in Earth's upper atmosphere and such techniques may also be suitable for the Venusian upper atmosphere.

## 3. Particulates

Some information will be gained in cloud composition from the Pioneer Venus mass spectrometer data but no direct detection of cloud composition will be attempted. This omission will be particularly important if some of the cloud layers are composed in whole or part of highly nonvolatile mineral or photochemically produced species. Of particular interest is the nature of the ultraviolet absorbing component in the visible clouds. Two possible candidate entry-probe experiments might be a particle collector/volatilizer connected to a mass spectrometer and an externally mounted X-ray source and X-ray fluorescence detector.

## 4. Atmosphere-Surface Interface

Chemical reactions between surface minerals and atmospheric gases are expected to be rapid at the high temperatures and pressures at the surface of Venus. Two important post-Pioneer questions are: (1) does the <u>exposed</u> surface contain those particular minerals (e.g., pyroxene, quartz, magnetite, calcite, halite, fluorite, tremolite, diopside, jadeite, ankamanite, andalusite, olivine, dolomite, troilite) expected if thermochemical equilibrium exists between the surface and atmospheric $CO_2$, CO, $O_2$, $HC\ell$, HF, $H_2O$, COS, and other gases? and (2) do gases which have been formed as a result of disequilibration by ultraviolet light in the upper atmosphere (e.g., $SO_2$, $SO_3$) react sufficiently rapidly at or near the surface to maintain the lower-atmosphere/surface region in thermochemical equilibrium? Resolution of these questions will obviously require a reasonably detailed analysis of the surface elemental composition, supplemented if possible by the detection of the dominant mineral phases.

5. Atmospheric Evolution

Part of the atmospheric evolution picture will be provided by the Pioneer mission, namely the present bulk composition of the atmosphere. Another part of the picture will be filled in when we understand in more detail the problems involved in upper atmospheric photochemistry discussed in category 2 and in thermal escape which lies in category 1. In addition, the problem of the evolution of the atmosphere is also intimately tied to the primordial volatile composition and outgassing history of the solid planet and to the chemical nature and time scales of atmospheric-lithospheric interactions. Thus the surface composition measurements discussed in 4 above, the problems concerning bulk planetary origin and evolution discussed in Sections I-B and I-C, and the exogenic effects discussed in Section I-D all have direct or indirect relevance to the problem of atmospheric evolution.

The absence of minerals required for surface/atmosphere equilibrium, or conversely the presence of minerals which could not be present in chemical equilibrium, will have obvious implications. Abundances of $^{40}K$, U, and Th will be relevant to the evolution of the $^{40}Ar$ and $^{4}He$ abundances in the atmosphere. The oxidation state of the surface is also significant. For example, if Venus accreted in the solar nebula at sufficiently high temperatures to exclude significant contributions by tremolite, serpentine, talc, and similar minerals to its primordial bulk composition, then the lack of water in the atmosphere is easily explained. As an adjunct to this, Venus would not be expected to have a highly oxidized surface; a major fraction of Fe should be present as $Fe^{++}$. On the other hand, if photochemical decomposition of $H_2O$ followed by thermal escape of $H_2$ is invoked, in order to remove water from the planet, the appropriate amounts of $O_2$ must be buried in the crust. Depending on the amount of water to be removed and on the rates of crustal overturn, a major portion of the surface Fe would be expected to be present as $Fe^{+++}$.

## F. ATMOSPHERIC DYNAMICS

The existence of 50-100 m/sec retrograde mean zonal winds in the Venus atmosphere is indicated by various spacecraft and ground-based observations. These winds are global and extend from above the visible clouds into the lower atmosphere, where they diminish in speed. Meridional velocities at latitudes below $\sim 50^\circ$ are less than 10 m/sec, at least at the altitudes observed by Mariner 10. Vertical motions have been measured to be as high as several m/sec at the locations of the USSR spacecraft Veneras 7 and 8, but it is unlikely such large updrafts extend planet-wide. Intense regions of turbulence have been measured by Mariners 5 and 10 at altitudes around 60 km, and between 40 and 50 km, the latter region corresponding to a level of high shear in the mean zonal wind profile measured by Venera 8. Ground-based measurements indicate small horizontal temperature contrasts, on the order of 5 K, at the altitude of the visible clouds.

Day-night temperature contrasts measured by Veneras 9 and 10 were higher (10-20 K). It seems reasonable to expect that at lower altitudes the horizontal temperature variations are significantly small. Knowledge of the atmospheric circulation therefore consists of several general characteristics, but considerably more information is needed to understand the driving mechanisms and processes that produce the wind patterns.

The principal dynamical questions that need to be addressed by atmospheric missions to Venus are the following: definition of global wind patterns; investigation of the driving mechanisms of the circulation, especially with regards to the 4-day zonal winds and including the effects of latent heat release and topography; the ways in which momentum and energy are transported around the planet; characterization and identification of planetary waves and assessment of their importance in relation to large-scale convective winds; and intensity and distribution turbulence and turbulent transport.

Pioneer Venus will provide information in most of these areas, but no single mission can address all the relevant questions. Post-Pioneer Venus missions should probably address, to various degrees, all the above questions.

Comparative meteorology between the planets known to possess atmospheres is important to attempts to construct general theories of atmospheric behavior and climatic change. Each of the planets presents unique combinations of the factors which influence planetary-scale circulations, and therefore each planet represents a distinct test of any general theory. Venus is unique among the planets in that rotational influences on the atmospheric motions are quite small.

## G. CLOUDS

When viewed in visible light, Venus is essentially featureless because of an almost uniform cloud cover extending from approximately 60-km altitude down to probably about 50 km. The composition and structure of these clouds have been investigated for many years, but only recently has a viable composition withstood comparison with most available experimental evidence. There is evidence for a number of cloud and haze layers extending about 20 km above the visible cloud deck, some of which are viewable only in the ultraviolet part of the spectrum.

Aside from interest in the clouds themselves, the determination of the composition and distribution of cloud materials in the atmosphere is important for at least two reasons. The horizontal and vertical distribution of solar heating, which drives the general circulation, and the thermal structure of the atmosphere are almost certainly determined to a large degree by the cloud material. Thus, an understanding of these phenomena is intimately involved with an understanding of the clouds.

There is considerable evidence that the visible clouds of Venus consist of a concentrated solution of sulfuric acid, approximately 75-85 percent $H_2SO_4$ by weight, which consists of particles about 1 micron in radius with concentrations of 10-100 $cm^{-3}$. The evidence for sulfuric acid clouds comes from determinations of the index of refraction and the infrared reflectivity as a function of wavelength; these measurements have been made from Earth and refer mostly to optical depth $\tau \sim 1$ ($\sim$ 70 km altitude). There are indications that the clouds are at least partially sulfuric acid at greater optical depths, but whether cloud composition is a function of altitude is not known. The lower boundary of the clouds appears to be located at about 50 km altitude, deduced from the nephelometers on Veneras 9 and 10.

Above the visible cloud deck, Mariner 10 observed a number of highly stratified limb hazes at about the 10-mb pressure level, having vertical thickness of about 1 km. There appears to be some horizontal variation in these haze layers with a length scale of about 1000 km.

The nature of the ultraviolet features observed in Earth-based photographs and the imaging equipment aboard Mariner 10 is as yet undetermined. The observation that small-scale features change on time scales of a few hours suggests that the light and dark markings are due to some condensible substance, but the composition remains unknown as well as the processes causing the variations. The altitude associated with the features is presently uncertain, but probably lies between 60 and 80 km.

Major scientific objectives with regards to the Venus clouds are the following: cloud particle composition, size, and number density as a function of altitude and possibly horizontal position; measurement of cloud optical and thermal properties; and possible condensation and precipitation cycles.

Understanding the nature of the Venus clouds leads to a better understanding of the overall chemistry of the atmosphere, which leads to increasing the number of constraints on atmospheric evolution and therefore planetary evolution. Furthermore, since the clouds may play a dominating role in the radiative energy balance of the atmosphere, they have to be considered in any possible attempt to model climatic change and atmospheric evolution.

# SECTION II

# PROPOSED MISSIONS AND SUPPORTING RESEARCH

## A. INTRODUCTION

The Pioneer Venus launches in 1978, probable Venera launches in 1978, and measurements by the Arecibo and Goldstone radars can be expected to give by 1980 a knowledge of Venus improved in several respects: atmospheric and ionospheric composition and properties above 135 km altitude; solar wind interaction characteristics; atmospheric dynamic patterns above the dense cloud layer at 65 km altitude; some lower atmospheric properties at a dozen or so probe locations; radioactive element abundances and local atmospheric and surface conditions at several places of unknown geologic context; estimates of broad variations of the gravity field and geometric figure; and near-global images of the surface at resolutions varying from 4 to 50 km.

To constrain circumstances of the origin of Venus, infer the main features of its evolution, and comprehend surface and atmospheric processes well enough to compare Venus and the Earth effectively, several questions will still remain in 1980: What is the bulk composition of Venus? How is this composition layered in the planet? What is the heat source content? What are the principal surface forms and the tectonic, atmospheric, and meteoritic processes affecting them? What is the composition of the atmosphere and its chemical interaction with the surface? What are the mechanisms of momentum and energy transport in the atmosphere and the resulting wind and wave patterns? How do the clouds interact with the composition and dynamics? What are the variations of the ionosphere and exosphere over the solar cycle?

The exploration of Venus must necessarily be responsive to two nonscientific factors. Firstly, there is considerable popular appeal in obtaining a comprehensive picture of the surface of the planet which is most like the Earth in size and distance from the Sun. Secondly, Venus has been the principal object of attention of the USSR's planetary exploration program. This Venera effort has been characterized by a large payload capacity but simple experiments and limited communication capability. Carrying more effective USA instrumentation and versatile telemetry on the USSR Veneras should be explored, so long as Soviet-American co-operation is a national policy. It appears that furnishing completed flight hardware would not be necessarily contrary to national technology transfer policy, which is concerned more about fabrication know-how. A natural objective would be an "International Venus Year," a combination of USA orbiters with USSR landers carrying some USA experiments launched during the excellent June 1983 launch opportunity.

## B. REQUIRED MEASUREMENTS

### 1. Interior

a. Seismometry. Most important is variation of seismic travel time with distance, from which can be inferred elastic properties, and thence something of composition and thermal state, as functions of radius: crustal thickness, size of core, etc. Ideally, measurements would require an array of seismometers, at least three, some hundreds of kilometers apart, on the surface for a duration which is uncertain because of the unknown seismicity level (perhaps weeks or months). The feasibility of detecting seismic events by hydrophones in the dense atmosphere should also be explored.

b. Heat Flow. Measurement at three or more locations selected by imaging radar reconnaissance is desirable to infer the energy content of the planet. The Venera 8, 9, and 10 gamma ray experiments indicate there may be significant lateral variations in heat flow, so multiple sites are desirable to get a good average.

c. Gravimetry. Lateral variations in the gravitational field indicate the level of tectonic activity, mantle convection, lithosphere-asthenosphere interactions, etc. A sampling thereof will be obtained by Pioneer Venus Orbiter near pericenter, but a global mapping from a more circular orbiter is desirable.

d. Altimetry. Variations in height indicate the level and nature of tectonic activity and, in combination with the gravity, the degree of isostatic compensation.

e. Magnetometry. Lateral variations in the magnetic field could imply the existence and nature of a hydromagnetic dynamo, if any, and thence indications of core composition and state.

### 2. Surface

a. Imaging. The observations of Venera 9 and 10 demonstrate the feasibility of acquiring images of the surface of Venus. Since photography has played a key role in our understanding of the surfaces of the other terrestrial bodies, it seems likely that future views of the Venusian surface will be of great benefit. The following are just a few of the types of studies which could be undertaken:

(1) Surface geomorphology: presence or absence of impact features, eolian erosional forms (dunes, streamers, yardangs) volcanic landforms (shields, cones, tubes, flows), and exotic phenomena (karst, solution or deflation hollows, fluvial forms, etc.)

(2) Surface materials and properties: search for rock types by albedo, color, or physical aspect; differentiation of clastic rocks, vesiculation, or other igneous textures; characterization of debris (sand, dust, gravels, pebbles, etc.).

Additional studies may be possible from balloon-borne imaging systems which would acquire data during periods of deep submersion into the atmosphere (i.e., from altitudes $\lesssim$ 10 km).

Observations from orbit will require radar techniques to penetrate the clouds. Global coverage at a resolution better than 1 km per pixel pair will allow questions concerning geomorphologic processes and relative time scales to be addressed. Selected regions imaged at resolutions ~50 - 100 m per pixel pair will allow studies of smaller-scale lithologic and environmental phenomena and characterization of the details to be generalized to the global imagery.

Required measurements are the following:

(1) Global : resolutions $\lesssim$ 1 km/pixel pair.

(2) Selected regions (~1 - 10% of planet): resolution $\lesssim$100 m per pixel pair (targeting capability).

(3) Low altitude observation: potential for imaging local areas from low-altitude balloons provides intermediate (0.5 - 10 m) resolution.

(4) Surface : isolated sites at very high ($\lesssim$5 mm per pixel pair) resolution.

b. Major Element Composition. Neutron activation or X-ray fluorescence techniques would determine the major constituents of the upper crust and thus increase the constraints on whole-planet bulk composition. Key questions include: the oxidation level (important to the chemical interaction with the atmosphere); the (K+Na):Fe ratio (pertaining to both volatile retention and the extent of crustal recycling); and the Mg:Fe ratio (also indicative of the degree to which the crust is differentiated). If possible, the measurements should determine compositional gradients and bulk densities.

c. Mineralogy. X-ray diffraction of infrared spectrophotometry would determine the nature of petrological reactions and further constrain the degrees of silica saturation, alkalinity, etc., as indicators of crustal recycling, bulk composition, etc.

d. Isotopic and Trace Element Abundance. Surface sample return is necessary to infer key aspects of Venerean evolution and its chronology.

e. Electromagnetic Properties. The electromagnetic (primarily dielectric) properties of the surface may be determined in three quite different ways: (1) by radar observation, where the surface reflectivity and thus the dielectric constant may be deduced from a knowledge of the strength of the radar echo coupled with a measurement of the radar scattering law; (2) by observation of the strength and polarization of the emitted thermal radiation coupled with a knowledge of the physical surface temperature; and (3) by an *in situ* (or returned-sample) measurement using standard laboratory techniques. Simultaneous data from all three techniques in selected areas would provide the necessary redundancy to lend credibility to the more widely dispersed results available from the first two alone. The first two techniques are applicable to orbiters which spend appreciable parts of their orbit below about 5000-km altitude; the last obviously requires a lander. A long-lived lander with a limited roving capability could also investigate near-surface electrical and magnetic properties using techniques developed for the Apollo Surface Electrical Properties (SEP) and Lunar Portable Magnetometer (LPM) experiments. The electrical properties of the surface are related to its chemical composition and to its bulk density. Any local variations in magnetic properties at the surface would indicate the presence of free iron, because the temperature is above the Curie point for the common ferromagnetic compounds.

f. Microstructure. Remote measurements of the angular distribution and polarization of radar echoes scattered from the surface may be used to deduce statistical information on small-scale slopes and wavelength-sized structure. Comparison of observed surface radio-emission temperatures with the corresponding physical surface temperature leads to an estimate of radio emissivity which, in turn, relates to the surface microstructure, provided the dielectric constant is known. Both of these approaches are intimately, in fact inseparably, related to the reductions required in applying the first two techniques described in the preceding paragraph or determining electromagnetic properties.

3. Atmosphere

a. Pressure and Temperature. Atmospheric structure should be determined in those regions of interest for which Pioneer Venus will give little or no information. In particular, such areas as the sub-solar point and polar regions should be explored, as well as the important altitude range between 65 and 135 km. Horizontal pressure and temperature variations drive the winds and should therefore be determined as extensively as possible.

b. Dynamics. The principal difference between post-Pioneer Venus atmospheric missions and Pioneer Venus should be the platform from which observations are made. In order to fully comprehend dynamical atmospheric processes, observations which are extended in space and time are required. For example, to study wind patterns and planetary waves, measurements must be made over a relatively long time, perhaps as long as several months. Thus, platforms floating in the atmosphere (e.g., balloons) are indicated for future missions. Remote measurements made from orbit, while capable of long observing periods, are unlikely to yield much more information about the atmosphere than will be obtained from the Pioneer Venus orbiter.

Instrument development for advanced missions should concentrate on the development of electronics capable of functioning at temperatures $\gtrsim$500 K. This would allow instrumentation capable of direct sampling for prolonged periods of the lower atmosphere, a region important for several reasons, including lower atmospheric circulation, cloud properties, composition, and atmosphere-surface interaction.

(1) Global wind patterns: Until the global circulation is better defined by observation, it will be extremely difficult to understand the dynamic meteorology of the atmosphere. Even though theoretical models of the circulation may exist, experimental determination of the wind patterns is essential.

(2) Drive for the circulation: Wind patterns themselves cannot lead to an understanding of dynamical processes unless the forcing functions to which they are the response are understood. Therefore, solar energy deposition as a function of horizontal position and altitude must be measured, as well as infrared radiative heating and cooling, and the pressure and temperature fields. In addition, the importance of latent heat release should be assessed.

(3) Atmospheric waves: Atmospheric waves are important in the Earth's atmosphere, and various features seen in ultraviolet photographs of Venus appear to be manifestations of atmospheric waves. Identification and characterization of planetary waves should be a goal of future atmospheric missions, and their importance to large-scale dynamics and cloud formation processes must be ascertained.

c. Cloud Properties. Further atmospheric missions should seek to quantify cloud properties with regard to composition, particle size, and number density as functions of position and optical and thermal properties. As is the case with atmospheric dynamics, Pioneer Venus should provide information in each of the above areas, but *in situ* measurements will be confined essentially to the locale of the large entry probe; direct measurement of cloud composition will not be possible, although inferences can be made from the data. Additional atmospheric missions could utilize either probes or balloons to extend cloud coverage planet-wide. Instrumentation should be developed to directly measure cloud composition, including the capability of analyzing solid particulates.

d. Gas-Phase Composition. Measurements of trace species concentrations in the unexplored photochemically active region above

65 km altitude should be given considerable priority (see Section I). Altitude profiles will be required for a number of gases whose concentrations are expected to vary significantly with height. These include $H_2O$, $HC\ell$, COS, $SO_2$, $H_2S$, $SO_3$, $H_2O_2$, CO, O, $O_2$, $O_3$, $NO_2$, and $HNO_3$. Measurements at 1-km altitude increments throughout the 65- to 135-km region and on both the day and night sides would be ideal. One measurement per scale height ( 5 km) beginning at the 65-km level and extending upwards as high as is feasible on the day side may represent a more attainable short-term goal. Measurements of the concentrations of short-lived species such as $C\ell$, $C\ell O$, $C\ell OO$, $OC\ell O$, OH, and $HO_2$ must be regarded as beyond our present scope, given the difficulty of detecting these same species even in the Earth's upper atmosphere.

Measurements of neutral spec· ·s in the regions which will already have been explored by Pioneer Venus (above 135 km, below 65 km) should be given secondary priority. Important new information that could be obtained from such measurements will relate primarily to understanding the three-dimensional and time variability within these regions. Great variability below 65 km is not expected, but there may be significant changes above the 135-km level, particularly between the day- and night-side hemispheres. The species to investigate and the appropriate experimental methods must remain similar to those in the Pioneer missions unless the forthcoming Pioneer data indicate otherwise. Extension of the range of any mass spectrometer to include mass numbers larger than the 208 limit of the Pioneer main probe instrument might be considered.

4. Ionosphere and Bow-Shock Region

The day-side ionosphere will not be as well understood as the night-side due to necessary constraints on coverage by the Pioneer orbiter and bus. In particular, ion composition in the 135- to 150-km region will be measured only at one position. Further measurements in this important region of the ionosphere are highly desirable. High interest, in situ measurements at these altitudes and above include electron temperature and density observations, neutral and ion mass spectrometer data, suprathermal ion observations with mass analysis, and magnetic and electric field measurements. The latter measurements would be used to determine the cross-field drift of plasma and the voltage imposed across the Venus ionosphere by the solar wind. Direct electron drift measurements might also be used. Extension of the range of the Pioneer Venus ion mass spectrometer to include odd mass numbers and mass numbers exceeding 56 may also prove fruitful. If the plasma wave survey instrumentation carried on board Pioneer Venus reveals that plasma waves play an important role in ionospheric processes, a more comprehensive wave instrument should be considered.

Remote sensing of the ionosphere using ionosondes and energetic electron tracers would complement the in situ measurements. The ionosonde would provide radial profiles of ionospheric density below the satellite on a global basis. Occultation data provides only occasional snapshots of the electron density profile. The electron tracer data would measure the magnetic field strength at approximately 100 km altitude again on a global basis in a similar manner to the survey of the lunar surface field using the particle instrumentation of the Apollo subsatellite.

In addition to extending our knowledge of the Venus ionosphere to lower altitudes, it is necessary to fill in the critical gap in our knowledge of the region from 1.3 to 8 Venus radii directly in front of and behind the planet that will remain after the Pioneer Venus mission. In front of the planet, direct coupling of the neutral atmosphere and the solar wind may occur due to charge exchange and photoionization. Behind the planet the magnetic field is stretched out in many respects similar to that of the earth and thus may be responsible for energization of plasma on the night side of the planet. The above-mentioned instruments together with a solar wind probe would be sufficient for this purpose.

## C. MISSION CONCEPTS AND PAYLOADS

To attain the principal science objectives in the exploration of Venus, four distinct types of missions appear to be technically feasible in the 1980-1990 time frame:

(1) Observations from orbiting spacecraft to provide global coverage (VOIR).

(2) Measurements by short-lived landers of atmospheric and surface properties at sites chosen on the basis of data generated by the orbiters. Auxiliary to these missions may be balloon systems for atmospheric monitoring (Venera, PAL).

(3) Measurements by long-lived landers which can survive on the surface long enough to have some probability of detecting seismic events and to attain equilibration after drilling for heat flow measurements (LIL).

(4) Return of surface and atmospheric samples for analysis in laboratories on the Earth (VSSR).

We assume that surface mobility would not be feasible within the time frame of this study.

On all missions, the priorities of experiments are indicated in parentheses: (1) essential to the mission; (2) important, to be carried if not significantly affecting priority 1 experiments; and (3) desirable, to be carried only if not affecting higher-priority experiments and if weight, power, and funding limitations permit.

### 1. VOIR: Orbiting Spacecraft

a. Rationale. Venus remains the one terrestrial body which has not been photographed at resolutions on the order of 1 km or better. Comprehensive coverage at 1 km resolution is necessary to map the principal landforms and thus infer something of their genetic and chronological relationships; selective coverage at 100-m resolution is necessary to determine most of the physical processes by which these landforms were created (e.g., whether sinuous rilles are lava or water features). To accomplish this mapping and sampling on Venus requires an orbiting imaging radar: VOIR.

The terrain information obtained by a VOIR will not resolve basic questions about the composition, internal structure, and evolution of the planet: these require surface landers. However, if Venus is like the Earth in the limited surface extent of key indicators of interior conditions and evolution (e.g., andesitic volcanism), then landers will be much more effective if targeted for certain terrain features. Therefore, orderly exploration of Venus requires imaging prior to surface sampling. A USA orbiting radar also would be more complementary to USSR Venus exploration if its development continues in current directions. A larger spacecraft in a less eccentric orbit would also permit more detailed atmospheric measurements than possible with Pioneer Venus.

b. Experiments

1) Imaging radar and altimetry (1). The task of providing high-resolution radar images of the surface-scattering properties of Venus is the backbone of this mission. Of substantial interest also is the determination of suborbital surface topography with a vertical resolution of better than 100 m and a lateral resolution comparable to that obtained in the imaging. The approach envisaged in this experiment uses a combination of resolutions in radar-echo delay, doppler frequency and angle to obtain continuous maps of the surface scattering over substantial portions of the globe. The technique has been thoroughly tested in ground-based observations of Venus (delay-doppler mapping) and in terrestrial airborne applications (side-looking radar). An Earth-satellite experiment (SEASAT) having a capability for observing the Earth not very different from that desired for the VOIR mission is scheduled for a May 1978 launch. The interpretation of the radar images in terms of planetary geology is essentially the same as the corresponding task for optical images.

What resolution is required? The best ground-based images of Venus using currently available facilities will have a resolution-cell size of about 4 km. There is an ultimate limit for ground-based observations of about 1 km, set by instabilities in the Venus atmosphere. On the one hand, our experience with Mars argues persuasively that with each improvement in surface resolution comes the ability to recognize entirely new geological phenomena; thus we press for the finest possible resolution, in expectation of full scientific value for the effort expended. On the other hand, we face technological limitations on what can be done. The primary limitation seems to lie in getting the data back to Earth, i.e., in the available telemetry bandwidth. In view of this conflict between the desired and the attainable surface coverage/resolution, a compromise must be sought. A possible mission design might yield global coverage at a resolution between 0.1 and 1 km (set by telemetry/mission-duration constraints), with supplementary coverage of a small, selected set of surface features at a resolution lying between 10 and 100 m. It would not appear difficult to obtain topographic information along the suborbital path, simultaneously with the side-looking imaging, using essentially the same radar instrumentation. This topographic coverage, of course, will not be as complete as the imaging, but would, nevertheless, be of substantial assistance in the geological interpretation of those images within which the topographic data lay.

2) Measurement of atmospheric composition, 65- to 135-km altitude (1 1/2). If no means can be found for in situ mass spectrometer analysis of the 65- to 135-km region, the compositional analysis of this region must be accomplished from the orbiter. A high spectral resolution visible-infrared spectrometer should be capable of some success in this task. In addition, use of spatial scanning should enable the vertical distribution of aerosols and certain gases (e.g., $HC\ell$, $H_2O$) to be ascertained.

3) Gravimetry by tracking transponder (2). The standard doppler tracking of the VOIR by the Deep Space Network (DSN) should obtain a resolution of gravity features roughly comparable to spacecraft altitude. Hence it is desirable to have an orbit of low pericenter and moderate eccentricity. However, data which are a significant improvement over Pioneer and Venera orbiters should be obtained from any VOIR capable of obtaining global radar coverage. The use of a subsatellite for gravity purposes should also be examined.

4) Radiometry (2). The absorption of centimetric radio waves (1- to 6-cm wavelengths) in the Venus atmosphere provides a means of measuring globally, from orbit, the effective temperature at several levels, particularly below the critical refraction level of 35 km. Weighting functions incorporating absorption vs altitude can be calculated for each observing wavelength and used to reduce the observed brightness temperatures to effective physical temperatures at known heights in the atmosphere. These, in turn, can be used to generate and verify models of atmospheric convection and of seasonal change. The use of two wavelengths, at approximately 1 and 3 cm, seems a reasonable choice to meet these objectives.

If radiometric observations at 10-cm wavelengths or longer are also included, information on the emissivity and/or physical temperature of the surface may be obtained. The observations of the surface at this wavelength should be made in each of two orthogonal linear polarizations, and, if possible, at several different angles of incidence to a given element of the surface. When combined with information on surface altitude, dielectric constant and smoothness obtained independently by the radar observations, the radiometric data become extremely powerful in testing our inferences concerning surface properties.

5) Ultraviolet (UV) cloud imager (2). Although aboard Pioneer Venus, UV imaging has the capability of yielding information on atmospheric dynamics, waves, and cloud properties and should be included. Improvements to Pioneer Venus UV images would be decreased time required to obtain global image and increased resolution.

6) Infrared (IR) sounder (2). Also aboard Pioneer Venus, this experiment is valuable to obtain temperature data to both correlate with dynamics and waves observed by UV imaging and to possibly correlate with UV cloud structure. Very-high-altitude temperature profiles can best be obtained using pressure-modulated or selective-chopping IR radiometers.

7) Measurements of particles and fields (2 1/2). Particles and fields experiments which might be considered include: neutral and ion mass spectrometers, electron temperature probe, retarding potential analyzer, electric field detector, magnetometer, swept frequency sounder suprathermal ion mass analyzer, solar wind probe, plasma wave instrumentation, and energetic electron tracer. Selection of these instruments for flight on VOIR should be based on their ability to fill gaps in knowledge remaining after the Pioneer Venus Mission.

8) Measurement of cloud properties (3). A UV spectrometer and cloud photopolarimeters are included in the Pioneer Venus Orbiter and should be included in the VOIR mission only if definitive new information can be shown to be gained.

2. VENERA: Large Short-lived Lander

a. Rationale. As discussed in the introduction, the USSR exploration of Venus has emphasized heavy landers with relatively simple instrumentation. Utilizing USA capability to provide instrumentation on a USSR lander would be a highly logical combination of capabilities.

b. Potential USA Experiments.

1) Measurement of elemental composition (1). Gamma ray spectrometry, neutron activation, or comparable instruments to obtain refinement of the U, Th, K abundances plus abundances (or abundance ratios) for two or more of the common elements. An isotopic neutron source, deployed on a boom and mechanically activated at landing, appears capable of exciting measurable gamma ray activity from Si, Aℓ, Mg, Fe, O, and Na. These experiments will also obtain estimates of bulk density.

X-ray diffraction or infrared spectrophotometry (2). At Venus surface temperatures, the infrared will be an emission, rather than a reflectance, radiation. It will still, however, be sensitive to crystal structure and composition, and thus diagnostic of mineralogy.

2) Measurement of atmospheric composition (2). It would be ideal if the lander could be decelerated sufficiently in the upper atmosphere to enable *in situ* analysis of the 65- to 135-km region. If such deceleration is possible, compositional analyses could be accomplished by a mass spectrometer and/or a gas chromatograph. Even if only one sampling at, say 85 km were to prove feasible, the results would nevertheless be extremely useful in understanding the photochemistry of the Venus atmosphere. The mass number range on the Pioneer Venus main probe neutral mass spectrometer (1-208) should be adequate for sampling purposes.

3) Measurement of Electromagnetic Properties (2). Measurements of the electrical and magnetic properties of a sample drawn from the surface of Venus would provide a measure of "ground truth" to validate the globally dispersed, but remote, observations made using radar and radiometric techniques on the Pioneer-Venus Orbiter and VOIR missions. These observations would best be done in direct contact with surface material, and might thus affect the spacecraft design. Hence the experiment should be designed, if possible, to be self-contained, even if thereby some degradation occurs. In addition to electric permittivity (including loss tangent) and magnetic permeability, the remanent magnetic field should also be measured in this experiment.

## 3. PAL: Probe and Lander, Light

a. Rationale. The Pioneer Venus probes will not provide a very complete sampling of the lower atmosphere, and it is uncertain whether the Veneras will measure certain important atmospheric and surface properties obtainable by USA instrumentation. It is probable that significant geochemical and mineralogical experiments can be done on a short-lived (about 1 hour) lander considerably sooner than the time scale required to develop the technology necessary for a long-lived (more than 20 hours) lander. Given this probable scenario, the next logical step after VOIR is a set of probes with short-lived landers. Decisions about some main features of the configuration, such as whether to use balloons or penetrators, must depend on further SR&T as well as project results.

b. Atmospheric Experiments. Future atmospheric missions to Venus should involve either floating platforms, such as balloons, or advanced probe concepts such as the zoom climb probe described in NASA TMX-62,450. Such missions would be capable of studying *in situ* regions of the atmosphere not accessible to Pioneer Venus e.g., the important altitude range between 67 and 135 km as well as critical regions such as the subsolar point and polar regions.

Possible instruments to be included regardless of the particular observing platform are the following:

Transponder (1): Tracking for wind measurement.

Temperature, pressure sensors (1): Structure and circulation.

Three-axis accelerometer (1): Wind and turbulence.

Net flux solar radiometer (1): Solar heating, which is the driving for the circulation.

Net flux IR radiometer (1): Infrared radiative heating and cooling.

Cloud composition detector (1): This instrument should measure cloud composition directly and should include the capability of measuring solid particulates. SR&T will be required to develop measurement techniques.

Nephelometer (1): Cloud scattering properties, cloud particle number density and size.

Cloud particle size detectors (1): Direct measure of cloud particle size. Possible instruments include particle impactors and particle size spectrometers.

Gas chromatograph and/or mass spectrometer (1): Atmospheric composition. Especially needed for *in situ* analysis of altitude region between 67 and 135 km.

Altimeter (2): Topography.

Magnetometer (2): Magnetic field mapping. Useful for studying ionospheric current systems as well as responses of the solid planet.

Electric field detectors (2): Cloud electric fields. Useful for studying precipitation cycles and cloud physics.

Sferics detector (2): Lightning discharge detector. Useful for investigating precipitation cycles which are known to be correlated with lightning activity.

c. *Surface Experiments.* Essentially the same complement of experiments should be considered as described above for the Venera lander plus those normally carried out by USSR:

Camera

Accelerometer, $10^{-6}$ g sensitivity

Thermometer, anemometer, barometer

In addition, consideration should be given to an active seismic experiment. While the depth to which it would sound may be limited, such an experiment would give some "ground truth" on near surface structure to complement radar evidence of such parameters as, for example, porosity.

4. LIL: Long-lived Lander

a. Rationale. Essential to an understanding of the interior structure and evolution of Venus is a better knowledge of its composition and state as a function of depth. The dominant technique for such determinations is seismology. However, the energy necessary requires natural seismic shocks, whose frequency of occurrence on Venus is quite uncertain. Hence it is desirable to maintain seismometers on the surface for as long as possible. Because measurement of heat flow would require drilling and time for thermal equilibration, this experiment probably would also necessitate a long-lived lander. Secondary benefits of an extended lifetime would be monitoring of atmospheric variations and more accurate elemental chemistry from longer counting times.

b. Experiments.

1) Seismometers (1). If Venus is similar to the Earth, then a sensitivity of $10^{-8}$g at a period of about 1 sec should gain useful information. Because of uncertain attenuation properties in Venus, it is desirable to get longer period performance as well as higher sensitivity. The optimum situation would be three seismometers, several hundred kilometers apart, to locate sources and resolve more propagation detail. However, valuable information could be derived by a single three-axis seismometer.

2) Heat flow measurements (1 1/2). The Venera gamma ray measurements and compositional considerations indicate about 60 ergs/cm$^2$/sec for the mean value of this fundamental parameter. The Venera measurements also suggest there may be significant lateral variation, so multiple sites would be desirable.

3) Other experiments (2). As foreseeable now, these would be essentially the same as for the short-lived landers. It seems inevitable, however, that there will be improved insight as to what are the best experiments as well as better instrumentation if there is a sound program of advanced technical research into, for example, high temperature technology.

5. VSSR: Surface Sample Return

By foreseeable techniques, any absolute chronology of the evolution of Venus would require return of a surface sample. Such absolute dating is particularly important because of the greatly differing surface conditions affecting Venerean geology. Any "stratigraphic" technique of relative dating is liable to be biased and difficult to relate to other planets. Sample return would also enable much more precise measurement of various trace element abundances diagnostic of past history.

The technical difficulties associated with launch from Venus probably would constrain the payload of any return to the extent that it should be largely or entirely devoted to the sample itself.

## D. SUPPORTING RESEARCH & TECHNOLOGY

The main SR&T problems arise from the high surface temperature and pressure, which stand in the way of attaining significant information about the lower atmosphere, surface, and interior.

### 1. VOIR-Oriented

The essential techniques for a Venus orbiting imaging radar appear to be well in hand; indeed, the main problem therewith is how to optimally process the excess of information bits which would be obtained by a radar for transmission back to earth. This is essentially an engineering development problem connected with DSN upgrading, adaptation of SEASAT data processing, and other communication technologies.

### 2. High Temperature

a. Basic. Vacuum tubes can operate at Venus surface temperatures, 740 K, but miniaturized semiconductor devices are needed to accomplish the amount of signal processing required for effective surface and lower atmosphere experiments. To assure the attainment of instrument potentials, investigation should be undertaken as soon as possible into materials and circuitry of electronic devices capable of operating at the 740 K temperatures.

Another area which should be investigated is the feasibility of refrigeration for critical parts of a surface lander and related general techniques of insulation and spacecraft configuration.

b. Applied. The nonelectronic essential elements of most of the experiments can, in principle, operate at the elevated Venus surface temperatures (e.g., the sources and detectors for the radiation experiments, the detector for the infrared spectrophotometry, the mechanical elements of the seismometer). However, specific instruments have not been operated at these temperatures. Inevitably, the characteristics of both the instrument and the measurables of the natural environment will be significantly changed. For example, the infrared spectrum, while still diagnostic of mineral composition, will be an emission spectrum rather than the reflectance spectrum used so effectively in planetary astronomy. Working out the best configuration for these surface experiments, particularly those indicative of composition in one way or another -- will probably require appreciable research and development prior to the start of the actual flight projects.

Another problem (not peculiar to Venus) of radiation experiments with active sources is the effect of these sources on spacecraft.

### 3. Penetrometers

There are two problems associated with penetrometers. First, because of their configuration (large surface area to volume ratio), penetrators would have usable lifetimes of only the order of minutes before current technology electronics would fail due to excessive temperature buildup from the surrounding high temperature environment. Second, because of the dense atmosphere, penetrators would need rocket-assistance to attain high enough impact velocity to penetrate the surface to depths of several meters. Therefore, although penetrators do not currently appear to be useful on Venus, the development of high-temperature electronics could make penetrators worth considering.

### 4. Drills, Seismometers

Techniques for sampling surface materials and ensuring long-lived surface activities should be studied and appropriate development initiated. Specifically, drills or other mechanisms for collecting subsurface materials (preferably documented) for onboard analysis or sample return or for deployment of subsurface geophysical instrumentation should be developed. Of the long-lived surface activities, seismometry seems most crucial to the study of Venus, and might well require the longest residence time. Mechanisms and/or techniques which allow prolonged operation at the surface of Venus are necessary. Possibilities include active cooling or phase change materials, high-temperature sensors and support electronics, or "bobbing" balloon-related stations which reside on the surface for a period of time and then return to the upper atmosphere to cool.

### 5. Balloons

Balloons offer several attractive features for observing the meteorology of the Venus atmosphere: direct coupling to the wind fields, long lifetime (at altitudes $\gtrsim$55 km with current technology), *in situ* measurements, and capability of releasing dropsondes at interesting sites. The major SRT effort required to enhance the attractiveness of balloons would involve increasing balloon lifetime at high temperatures so that balloons would have the capability of investigating the lowest scale heights of the atmosphere.

6. Surface Sample Return

This return apparently would entail a multistage launch, the first stage of which would be a balloon ascent to as high an altitude as feasible before undertaking a rocket launch. This research and development should be paced so as to allow a decision around 1984-1985 on the priority between a long-lived surface lander (LIL) and sample return (VSSR).

7. Solar Sail

While this development will be driven mainly by missions to other planets, the payload enhancement on Venus missions by sail techniques should affect decisions in the mid and late 1980's regarding LIL and VSSR.

## E. OTHER VENUS-DIRECTED OBSERVATION AND RESEARCH

1. Earth-Based Observations

Radar measurements by the Goldstone and Arecibo radio telescopes have already imaged structures on the scale of a hundred kilometers or more on the Venusian surface. Some appreciable improvement is anticipated by upgrading of telescope capability, as described in the Introduction. Modifications to the Arecibo telescope will enable imaging of 25-50 percent of the hemisphere of Venus facing Earth at inferior conjunction with a resolution of 4-8 km per cell. It is improbable that Earth-based radar will yield significant data for the hemisphere facing away from Earth during inferior conjunction, a serious deficiency in light of the known morphological asymmetries of the Moon, Mars, Mercury and the Earth.

Other ground-based observations involving microwave radiometry, infrared reflectance spectroscopy, polarization measurements of reflected radiation, and mapping of brightness temperatures in the infrared may make auxiliary contributions to our knowledge of atmospheric and cloud composition, cloud particle characteristics, and temperature contrasts in the atmosphere.

2. Laboratory and Theoretical Studies

For effective interpretation of measurements by atmosphere and surface experiments proposed for space missions, complementary laboratory measurements are required; in particular:

(1) Emission spectroscopy of minerals at high temperatures (~700 K).

(2) High-temperature kinetics of $CO_2$, CO, COS, $SO_2$, $H_2S$, $HC\ell$, HF mixtures above, and at, appropriate mineral surfaces.

(3) Laboratory spectra of relevant gases in the infrared and microwave regions.

Theoretical models of appreciable complexity will also be required to attain the maximum improved insight from Venus-directed measurements. These include:

(1) Dynamics and general circulation of the atmosphere.

(2) Thermochemistry and physics of clouds and aerosols.

(3) Interaction of the solar wind with the ionosphere.

(4) Structure and thermal evolution of the interior.

## F. PRIORITIES AND SCHEDULE

Launch opportunities to Venus occur at approximately 19-month intervals. The qualities of launch opportunities occurring within the time frame of this study are:

1981 November: good

1983 June: excellent

1984 December: excellent

1986 August: good

1988 March: poor

1989 November: excellent

Flight time from the Earth to Venus is about seven months without solar sail.

While a VOIR launch is feasible at the November 1981 opportunity with an FY 1978 project start, a June 1983 launch not only would be more realistic (given other missions and plausible funding levels) but would take better account of Pioneer Venus results in its planning. For this launch, the project start could be at the beginning of FY 1980, provided that SR&T on the onboard processing of the radar imagery information is started a year or so earlier.

If an "International Venus Year" with US instrumentation on a Venera lander is to be achieved in 1983, then political negotiations should be undertaken as soon as practicable. The hardware project should start by early FY 1979, allowing an extra year or so for the difficulties of international collaboration.

To preserve options and maximize potentials for missions in the late 1980's, both high-temperature and surface sample return SR&T should be undertaken as soon as practical.

By early 1982 Pioneer Venus and Venera results, experience in collaborating with the USSR over USA experiments on the 1983 Venera lander (or the absence thereof), and five years' SR&T should furnish a sound data base for the nature of a probe and lander project to start early in FY 1983 for an August 1986 launch.

To take advantage of the November 1989 launch opportunity, the decision on long-lived lander (LIL) vs sample return (VSSR) would have to be made in 1984.

The main milestones are given in Table 1.

Table 1. Venus Exploration

| | |
|---|---|
| FY 1977 | Start negotiating collaboration with USSR |
| 1978, May, Aug. 78 | Launch: Pioneer Venus, Venera |
| 1979, Oct 78 | Start SR&T: high temperature, sample return |
| 1980, Oct 79 | Start: Project → June 83 launch<br>VOIR = Orbiter → Surface morphology, upper atmosphere composition |
| 1983, Dec 82 | Start: Project → Aug. 86 launch<br>PAL = Probe & Short-lived Lander → Surface composition, atmospheric dynamics |
| June 83 | Launches: VOIR, Venera<br>IVY (International Venus Year) |
| 1984, Jan 84 | 1st RESULTS: VOIR, Venera |
| 1985, May 85 | Start Project → Nov. '89 launch<br>LIL = long-lived lander → seismology<br>OR VSSR = sample return → isotope and trace geochemistry |
| 1986, Aug 86 | Launch: PAL |
| FY 1990, Nov 89 | Launch: LIL or VSSR |