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Proceedings of a workshop held at
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Pioneer Venus 12.5 km Anomaly Workshop Report (Volume I)

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Summary

A workshop was convened at Ames Research Center on September 28 and 29, 1993, to address the unexplained electrical anomalies experienced in December 1978 by the four Pioneer Venus probes below a Venus altitude of 12.5 km. These anomalies caused the loss of valuable data in the deep atmosphere, and, if their cause were to remain unexplained, could reoccur on future Venus missions. The workshop participants reviewed the evidence and studied all identified mechanisms that could consistently account for all observed anomalies. Both hardware problems and atmospheric interactions were considered. Based on a workshop recommendation, subsequent testing identified the cause as being an insulation failure of the external harness. All anomalous events are now explained.

Introduction

The Pioneer Venus probe mission has been widely recognized in the atmospheric science community as highly successful and productive. It established a new level of knowledge of the upper, middle, and lower atmospheres of Venus, replacing in many instances uncertain knowledge or speculation with measurements and observations. Areas in which there were major advances included thermal structure and stability of the atmosphere, cloud altitudes, particle densities and sizes, composition (major and trace species), horizontal winds and vertical velocities, the detection and characterization of wave systems, and the penetration and balance of solar and thermal radiation.

The anomalies that were the subject of this workshop were unexplained behaviors of the external sensors at and below 12.5 km altitude. Below this common altitude, instruments outside the sealed pressure vessels exhibited problems on all four probes. Indicated temperatures dropped discontinuously, but the sensors continued to report data (ref. 1). Net flux radiometers showed a sudden decrease in the net flux toward zero and a nearly discontinuous increase in atmospheric temperature (ref. 2). Box cover status signals, on boxes from which the temperature sensor and net flux radiometer had been deployed on the small probes, indicated the sensors had, impossibly, been restowed. Large probe thermocouple wires, which had been cut prior to jettisoning of the heat shield at parachute deployment, indicated signals of a few millivolts. These observations were not consistent with known variations in the atmospheric parameters, but must have represented difficulties in the proper operation of the external instrumentation.

In the year after encounter, limited investigations of possible hardware causes of these anomalies were conducted at Hughes Aircraft Company, the probe contractor. No cause for the anomalies was identified. The project office sponsored a theoretical study at San Jose State University, which focused on sulfuric acid corrosion of the platinum temperature sensors (ref. 3). The predictions of this study were not entirely consistent with the observations and did not explain other occurrences, including the simultaneous fall to zero of the measured net flux. Over the years, no further concerted attention was given to explain what happened.

Now, missions to return to Venus are under consideration as candidate missions in the Discovery program. This gives renewed importance to understanding what caused the 12.5 km anomalies, because not understanding them may raise the possibility that they could reoccur.

The Anomaly Workshop was convened at Ames Research Center to attempt to resolve what caused the anomalies. The workshop brought together probe system engineers from Hughes Aircraft Company; project office personnel (some now retired); probe scientists; instrument designers of the affected instruments; and other atmospheric scientists including chemists, dynamicists, and electrodynamicists. Participants were:

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William Pitts	Ames Research Center (ret.)
Louis Polaski	Ames Research Center (ret.)
Boris Ragent	San Jose State University Foundation
David Rider	Jet Propulsion Laboratory
Victor Rogers	Hughes Space and Communications Company
Robert Ryan	Jet Propulsion Laboratory
Alvin Seiff (convener)	San Jose State University Foundation
Simon Sommer	Ames Research Center (ret.)
Larry Sromovsky	University of Wisconsin
James Willet	Jet Propulsion Laboratory
Richard E. Young	Ames Research Center

The agenda included: (1) a critical review of the anomalies of both the experiments and the spacecraft; (2) presentation and evaluation of candidate hardware explanations; (3) presentation and evaluation of candidate atmospheric phenomena as explanations. Subpanel meetings and workshop discussions were used to arrive at conclusions and recommendations.

In this report, a background is given to explain how the probes were configured and to describe the nature of the anomalies. A summary of presentations made in the meeting and the accompanying outside analysis are included. Finally, the conclusions and recommendations are presented.

The viewpoint taken is suddenly historical. That is, the ideas are reviewed as they happened, and explanations since disproved are described to indicate the sequence of arguments through which the problem became better understood.

Thanks are due to all participants who contributed major written input to the proceedings. Particular thanks are due to Louis Polaski for his early efforts to catalog and describe the apparent anomalies; to the current and former Hughes Aircraft Company personnel who attended the workshop and contributed their invaluable memories and interpretations; and to Scott Hubbard and Lawrence Lasher who gave invaluable assistance in organizing and making the workshop possible.

Background and List of the Anomalies

The Pioneer Venus small and large probe configurations are shown in figure 1. A small probe is shown in exploded view in figure 1(a), with the pressure vessel separated from the heat shield and the atmospheric temperature sensor and the net flux radiometer deployed from the sensor boxes mounted on the back sides of the pressure vessels. In descent to Venus, the heat shields were retained and the probes were in free fall (i.e., they did not deploy parachutes). In contrast, the large probe deployed a parachute and jettisoned its heat shield at the cloud tops. The parachute was released at 44 km so that in the deep atmosphere, the configuration was as shown in figure 1(b). The temperature sensor, the mass spectrometer and pressure inlets, and the windows and optics used by the cloud particle spectrometer and two radiometers were exposed to the atmosphere when the aeroshell was jettisoned. Thus, the small and large probes at and below 12 km differed in both configuration and external materials. The large probe was just the titanium pressure vessel with a spherical windshield of sheet titanium, called the "aerofaring." The small probe titanium pressure vessels were nested behind the retained blunt-nosed, conical, carbon phenolic heat shields. Within the spherical titanium pressure vessels, there was a benign, low-temperature-pressure environment for all components not required to be in contact with the atmosphere.

A list of the anomalies below 12.5 km as summarized by Fimmel et al. (ref. 4) is given in table 1. Because of design and instrument payload differences, many of the small probe anomalies were not applicable to the large probe and vice versa. Table 2 is a condensation of a similar list given by Polaski (ref. 5) and presented at the workshop to emphasize that probable causes exist for the first four anomalies. These were considered by the presenter (A. Seiff) to be well enough documented that they could be regarded as explained. The primary unexplained observations were items 5 through 11 in table 2. While the two science instrument anomalies are of principal interest, a number of lesser, but puzzling, unexplained events are noted in these tables. It is noteworthy that sensors inside the probes, including the optical radiation and cloud detection sensors and the mass spectrometer, continued to give valid data below 12.5 km to touchdown.

These anomalies were discussed in greater detail by individuals having greatest familiarity with the data and hardware components.

Net Flux Radiometer Anomalies (Summary of presentation by L. Sromovsky)

Between 1800 and 2000 sec from entry, the indicated net fluxes from the three small probes (fig. 2, open circles) became anomalous, falling essentially to zero within a few sample intervals. Simultaneously, the net flux radiometer (NFR) temperatures (filled circles) departed from their prior rate of increase and either rose steeply to apparent saturation levels or, in the case of the night probe, first plunged to an indicated 350 K and then rose to saturation. The timing of these events differed by no more than 100 sec from anomalies experienced by the atmosphere structure instrument temperature sensors.

Calibration signals from the NFR electronics were stable through the anomalous data period, indicating that the anomalies were not caused by an electronics failure.

The last valid NFR temperature readings from small probes 1, 2, and 3 were 631, 633, and 635 K, respectively. These are within 2–9 K of the temperatures at which the atmosphere structure instrument (ASI) breakdowns occurred. The net flux data and the temperature data became anomalous nearly simultaneously. The temperatures went from normal to anomalous in ~96 sec (3 data samples). The net flux signals, normally approximately tenths of a millivolt, dropped to near 0 mv, suggestive of shorting of the signal leads.

Unlike the ASI temperatures, the NFR-indicated temperatures generally increased as a result of the anomaly (ref. 6). This would suggest increased resistance of the sensing element or, possibly, resistive contact of the signal leads with an outside voltage source, such as the heater power supply voltage (on a lead within the same cable).

During sensor development, the NFR sensor heads, excluding the Hughes harness, were tested at elevated temperatures. Insulation resistances between sensor leads and sensor ground typically dropped from $>10^8$ ohms at room temperature to as low as 3×10^5 ohms at 684 K. Other insulation resistances were similarly reduced by elevated temperatures. These values were considered satisfactory for accurate readings. Some tests were performed in CO_2 at atmospheric pressure at temperatures up to 773 K. Others were performed at pressures up to 90 bars at high temperatures in a nitrogen environment. But the sensors were never tested at conditions that fully simulated Venus at and below 12.5 km (i.e., in CO_2 at temperatures of 640 K or higher and at pressures of 40 bars or higher).

Atmosphere Structure Instrument Anomalies (Summary of presentation by A. Seiff)

The ASI temperature (T) sensor "breakdowns" are illustrated in figure 3 for the large and north probes. The drop in indicated temperatures near 2200 and 1950 sec from start of descent is nearly discontinuous. The drop-offs occur in approximately 1 sample interval, which is 2 sec for the large probe and 16 sec for the north probe. Data from two independent sensors, T_1 and T_2, were both affected. The latter was electrically insulated from the atmosphere.

Conditions at the ASI T sensor breakdowns were substantially the same on the four probes (table 3). Atmospheric temperatures were between 627 K and 640 K (lowest for the large probe) and pressures were between 36 and 40 bars.

The temperature sensors were platinum resistance thermometers with room temperature resistances of ~10 and 14 ohms. Sensor resistances were measured precisely during descent by a 4-wire ohmmeter circuit to define their temperatures. T_1 was a 100 micron platinum wire, wrapped around an insulated platinum-rhodium frame and open to the atmosphere. T_2 was a 25 micron wire raster mounted on the same frame over a glass film on the windward side of the outermost platinum tube and covered by a thin insulating glass film. As shown for the north probe in figure 3, the two independent sensing channels, T_1 and T_2, broke down simultaneously. After reaching a minimum reading, reported temperatures partially recovered to values ~0.7 to 0.9 those expected.

In calibration to a maximum temperature of 643 K, the sensors functioned normally. The complete large probe descent configuration was tested in a simulation of expected temperatures as a function of time up to a maximum of 725 K in September 1977 prior to the probe final design review. This test was at atmospheric pressure in air. Instruments were operating during the test, and the temperature sensor functioned normally. A maximum temperature of 725 K was registered by T_1, and the two sensor channels agreed within a few degrees. Pressure vessels were qualified structurally in separate tests. By project and probe contractor decision, tests simultaneously simulating the pressures and temperatures of the Venus deep atmosphere were not performed. There was no equipment to reproduce Venus surface conditions for the complete probes or temperature sensors. The development of such test facilities was recognized to be a costly undertaking because of safety problems associated with a large chamber heated to 500°C at 1500 psi internal pressure. This test would have impacted the schedule and cost on a program run in much the same spirit as the present Discovery program.

The sensor breakdown at 12.5 km was similar in some respects to the shorting of T_1 in the sulfuric acid clouds above 50 km (fig. 3(a)). In both cases, the T_1 readings dropped well below ambient atmospheric temperature; at 12.5 km the onset was more precipitous and the T_2 element, though insulated from the atmosphere, was affected as was the exposed element, T_1. This similarity suggested the possibility that the sensor elements were partially shorted in the deep atmosphere.

The T_1 sensor behavior in the clouds was a result of diversion of some of the excitation current around the sensing element by a short, created by a conductive film or droplets of sulfuric acid on the free wires and the sensor frame. In the period of anomaly, the observed data behavior can likewise be explained by shorting or the diversion of excitation current in *both* sensor channels. The shorting could have occurred: (1) within the sensors; (2) in the harness wires, particularly those external to the probes and subjected to the atmospheric environment; or (3) by a deposit of conductive material from the atmosphere. This possibility will be further discussed in a later section. A resistance ~1000 ohms from the excitation current leads to probe ground would produce the observed effect on the data.

Sensor internal insulation resistances were normally in the range of 10^6 to 10^{10} ohms. Insulation resistance was adversely affected in moist environments, going to values as low as 50,000 ohms. Values greater than 10^6 ohms were recovered when the sensors were dried in vacuum. After the final calibration of the Venus sensors at Ames in April 1977, the sensors were dried in vacuum at ~40°C for ~60 hours. Test data taken in Florida prior to launch gave correct temperatures. The long exposure to the vacuum of space during cruise, and the hot, dry Venus atmosphere during descent would further contribute to high sensor insulation resistance.

A second kind of anomaly in the ASI data listed by Polaski and Fimmel (refs. 4 and 5) was a series of unexpected jumps in pressure sensor offsets. The jumps occurred at atmospheric pressures less than ~20 bars, i.e., at altitudes above 20 km (ref. 7), and were caused by the bursting of low-range sensor diaphragms at high overpressures. The sensors were inside the probe pressure vessels. They sensed pitot pressures conducted by a manifold open to the outside atmosphere. The offset jumps were a result of current leakage in the solid state switches that selected the on-range sensors and are considered to be satisfactorily explained.

Nephelometer Observations in the Anomaly Period (Summary of presentation by B. Ragent)

The third instrument on each small probe was a nephelometer that was used to sense the presence of particulate matter in the atmosphere. This instrument also incorporated radiometers to sense ambient radiation at 365 and 530 nm. The large probe also carried a nephelometer. The instruments were inside the pressure vessel. The nephelometers viewed the outside atmosphere through side-view windows located on the afterbodies of the small probes, figure 1(a), which were not directly exposed to atmospheric flow. The nephelometer data below 12.5 km were normal and appear valid.

An unexpected observation in the nephelometer data was the detection of small backscatter signals in a layer about 0.25 km deep near 6 km altitude by the two nightside probes (ref. 8), indicating the presence of a particle-bearing layer. These signals have not received much attention, nor have they been explained. A second observation was the detection of UV and IR radiation below 15 km by the background radiation detectors in the two dayside probes. The intensity increased with depth. This radiation was explained as atmospheric thermal emission leaking through the detector filters. No unusual variations in light signals were seen, which could be due to chemical reactions (e.g., burning) in the near vicinity of the probes.

Other Probe Anomalies

Other probe anomalies listed in table 2 include thermocouple and cold junction temperature anomalies, a sizable decrease in the large probe bus current at 11.5 km, a "booms-restowed" indication from all six small probe deployment mechanisms, small step changes in communication system parameters, and changes in large probe internal temperature and pressure.

These observations help reveal the nature of the phenomena causing the anomalies.

1. The booms-restowed indication was received on the three small probes at the next switch status reading after ASI temperature sensor breakdown (within 64–224 sec). This anomaly was previously explained as a result of shorting of the switch contacts by collapse of the microswitch case at high pressure and temperature (ref. 9). Two alternative explanations were discussed, but dismissed: (1) breakdown of harness insulation resistance to ~2500 ohms, at which time the electronics would indicate that the switch was closed; and (2) electrostatic damage to the multiplexer chip, which routes the status signal to the command and data unit (CDU) (ref. 10). This explanation was somewhat discredited by Buterbaugh (ref. 10) because the CDU was also susceptible to static damage and survived the anomaly period.

The boom-status switch was provided to verify that the ASI and NFR booms were deployed at the *start* of descent (i.e., above 60 km altitude); survival to the surface was not required. Two post-encounter tests of the switch in a programmed simulation of increasing pressure and temperature in descent were described in a Hughes interdepartmental memo (ref. 11). The tests were consistent in showing switch failure at a pressure of 60 bars at temperatures of 486 K in the first and 716 K in the second test. This is the pressure at 6.5 km altitude on Venus—an altitude reached 6–8 min later in the descent than the booms-restowed signals were transmitted. An unresolved question in the second test was whether the failure was caused by pressure or by temperature degradation of the potting compound. If the failure was caused by the latter, failure pressures greater than 60 bars would be indicated. Hence, switch failure by collapse at 40 bars (12.5 km) is not consistent with the test data, and other possibilities for the change in switch state, including harness shorting, remain viable.

2. The three small probe cold-junction thermistor signals behaved anomalously shortly after the ASI T sensor breakdowns (ref. 5). The thermistors defined cold-junction temperatures for the thermocouples embedded in the heat shield. They were located on a terminal board mounted on stand-off posts on the back face of the aeroshell in a space vented to the atmosphere. Gas flowed into this space to maintain atmospheric pressure as the probes descended. At the time of ASI T sensor breakdown, all of these thermistors were reading full-scale temperatures (505 K). Within 4.5 min, however, readings dropped to incredibly low values (e.g., a minimum of 194 K on small probe (SP) 1), but recovered to full scale again over an additional 6 min. In an interdepartmental memo to C. M. Meredith (ref. 10), J. N. Buterbaugh concluded that the most likely cause was "insulation failure or contamination of the connector pins associated with their harness." The degraded insulation resistance to reproduce the minimum indicated temperature is 2650 ohms, a value similar to that required to explain the boom microswitch failure and the ASI T sensor breakdowns. Buterbaugh also discussed electrostatic damage to the electronics as a possible cause, but concluded that it was not a tenable explanation.

If partial shorting is the explanation for the drop in thermistor temperatures, the recovery of the indicated temperatures to full-scale values would require either that the short resistance increase with time to ~8000 ohms or that a resistive connection to a power lead within the cable develop, a mechanism proposed by Buterbaugh to explain the large probe thermocouple anomaly and by Sromovsky to explain the NFR temperature anomaly.

3. There were two thermocouples in the large probe heat shield to monitor its performance, one near the stagnation point and one near the conical base. Leads from these thermocouples were severed before the heat shield was jettisoned at the start of descent (above 66 km). The cut ends were retained within the cable cutter housing on the descent module. Starting at about 15 km altitude, signals of 1 count or 0.2 mv appeared in both sets of leads, increasing for one sample to 2 counts, then holding steady on the stagnation point sensor but returning to 0 on the sensor located near the conical base. Near 8 km altitude, the stagnation point sensor registered a series of 1 count increments in signal at 2–3 min intervals, accumulating a total of 6 counts or 1.2 mv. The other sensor accumulated 2 counts or 0.4 mv.

It has been proposed that these signals might have been induced by interaction of the cut wires with a plasma of unidentified origin around the Probe. However, the wire ends were isolated from an external plasma by being enclosed in the cable cutter. A second explanation (ref. 10) is that the cut ends came into resistive contact with other wires within the anvil carrying 28 volts, which were also part of the cable severed by the cutter. At the preflight final design review in June 1976, this possibility was somewhat anticipated by notes on page 81 of the System Interfaces presentation (ref. 12): "Large Probe

Cable Cutter Could Cause Conductive Shorts" and below that, "Present Design Offers Ample Protection Against Shorts." Although it cannot be confirmed, this seems to be a completely adequate explanation for the observed signals. Changes in signal with altitude could result if the wires moved because of thermal expansion as the system was heated by the atmosphere.

4. A large step decrease in large probe bus current (2.12 amps) occurred at 11.5 km altitude. This current step corresponds to the second stage window heater current provided to keep the window of the infrared radiometer instrument clear of condensates, and implies that the heater either burned out or shorted to its housing, which would have burned out the fuse. The nichrome heater was insulated from its tantalum tube housing by a minimal, 0.006-in. layer of magnesium oxide. A number of problems leading to both shorts and open circuits in the heater had been experienced during development (refs. 13 and 14), and it is quite conceivable that the heater failed in descent under the stresses imposed by the lower atmosphere temperature and pressure environment. Given these circumstances, this should not be considered an unexplainable anomaly.

5. The anomalous steps reported in large probe internal pressure could not be found in a current review of the data. Internal pressure progressed in resolution-limited steps of 0.21 psi to increase smoothly from 19.0 psia at the start of descent to 27.27 psia at touchdown. Similarly, the internal temperature increased in discrete steps of 0.8°C (forward shelf) and 1.14°C (aft shelf) corresponding to the measurement resolution. The temperature envelope increased smoothly and continuously. There was no anomaly requiring explanation.

6. Anomalies listed by Polaski (ref. 5) in the large probe radio communications system were analyzed by N. Wong (ref. 15) and for the workshop by Peter Garriga of Hughes, who reported that there were 1 count steps in the automatic gain control (AGC) and in the static phase error of the transmitter at 39 min after entry (approximate altitude 9 km). The static phase error has a temperature sensitivity of 1 count/6°C, which could account for its one-step shift. Doppler tracking of the probes required receiving signals from Earth and retransmitting them. Probe dynamics (ref. 16) coupled with ripples in the antenna pattern could account for one-step changes in the AGC. Conclusion: Nothing outside the limits of normal operation occurred.

In summary, of the listed probe anomalies, several are within limits of normal operation or have logical and credible explanations. Only the booms-restowed indication and the thermistor behavior cannot be accounted for with assurance, but there are quite believable explanations for these two as well. The consistent theme that explains these and ASI and NFR anomalies is that all would be accounted for by degradation in harness insulation to $\sim 10^3$ ohms. However, this has not been demonstrated beyond reasonable doubt, nor has it been refuted by definitive tests.

Harness Studies

Immediately after probe encounter in December 1978, the possibility was raised that insulation breakdown in the probe external harness at the high pressure and temperature on Venus at 12 km could have caused the anomalous behavior of the external instruments (ref. 17). This prompted a reexamination of the harness testing conducted prior to flight and to additional tests.

Preflight tests of the two external cable types were performed in May–June 1976. Tests were in nitrogen at temperatures up to 760 K and pressures up to 100 bars. Insulation resistance $\geq 10^6$ ohms was recorded at 645 K. Because of practical difficulties of achieving the desired pressure and temperature from bottled CO_2, it was not used in these tests. Both CO_2 and N_2 were considered to be chemically inert, so the substitution of N_2 was considered satisfactory.

Kynar shrink tubing was used to cover the single-pin Cryocon connectors used to connect both the ASI and NFR sensors to the harness. Tests showed that Kynar "degraded to ash" at $T \leq 750$ K in 1 atm of N_2, but this was said not to impair insulation resistance (ref. 18).

The effects of the sulfuric acid in the clouds of Venus on kapton, the polyimide film used to wrap the external harness, were not simulated in preflight testing. After the probes encountered Venus, Hughes Space and Communications Company consulted DuPont Chemical Corporation, the manufacturer of kapton, about sulfuric acid effects and were told that kapton is embrittled by long-term exposure to sulfuric acid (ref. 18). In February 1979, three months after the encounter, Hughes tested harness specimens with sulfuric acid exposure. The test cable was coated with 96 percent acid applied as droplets from a pipette and cotton swabs were used to distribute it. The cable was then quickly tested (within 9 min), and subjected to a programmed increase of pressure and temperature using N_2 as the test gas. Insulation resistance measured during the test remained at $>10^6$ ohms after 35 min (simulating the time at 12.5 km), but dropped to 1.5×10^5 ohms after 60 min when pressure was 760 K and 100 bars. After the test, inspection showed the outer kapton layer to be essentially "removed by the acid" (refs. 9 and 19).

The substitution of N_2 for CO_2 may not be benign, as assumed, because equilibrium chemical calculations show that CO_2 at 40 bars and 640 K is, for some substances, an oxidizing agent. It oxidizes titanium, yielding TiO_2 and CO. Kapton, a long chain organic polymer with an abundance of oxidizable H atoms appended to a central carbon chain, may also oxidize in CO_2. That is, kapton may "burn" in CO_2 at high pressure and temperature.

Post-Encounter Studies by Goodman and Albert

Goodman and Albert (ref. 3) examined possible explanations for the ASI temperature sensor breakdown, but not the more general problem of explaining all observed anomalies. They considered and evaluated five mechanisms for atmospheric electrification. One mechanism was localized chemical gradients giving rise to local electrical discharges, with the gradients being generated by decomposition products diffusing from the carbon phenolic heat shield at 570–620 K. Citing a Hughes report, they state that between 2 and 10 g/min of gases will be evolved. However, they reach the conclusion, "It is evident that malfunction of the probe was caused by a phenomenon other than a direct electrical discharge." (See section by Borucki for further comment on this possibility.)

They performed a study of collection efficiencies for H_2SO_4 cloud particles of the complete probe and of the T_1 wires. The efficiency for the probes was 0, but was 0.93 for the wires (the mass of acid collected by the wires in vertical transit through the clouds was calculated to be 0.14 mg/cm of wire length). They argued that the acid would wet and evenly coat the wires with a film.

Goodman and Albert considered evaporation of the collected acid below the clouds, and, because water evaporates preferentially, found that the acid would concentrate. Starting with 80 percent acid, the concentration reaches 90 percent to 100 percent at altitudes of 25–40 km. (Note: The ASI data showed that acid was cleared from the free wires earlier than this (i.e., shortly after large probe parachute jettison). This was explained by Seiff et al. (ref. 7) as removal by the mechanical action of the wind, i.e., by shear and pressure forces.)

Scanning the range of possible further reactions, Goodman and Albert considered metallic chlorides that could adhere to and dissolve in the acid film. The concentrated acid would, they stated, adsorb any H_2S present and reduce it to sulfur. These dissolved materials would possibly embrittle the platinum wire. They cited a reference that stated the platinum was slowly attacked by hot, concentrated sulfuric acid and formed hydrated $Pt(SO_4)_3 \cdot n(H_2O)$. The concentrated chemical film could, they speculate, "cause the thin glass insulating layers to crack or rupture and short out the temperature sensor," referring to the bonded sensor T_2 (stated without proof).

Goodman and Albert also discussed the reactivity of tantalum (used in the large probe infrared radiometer (LIR) window heater) with sulfuric acid and concluded that it is unlikely to have caused failure because sulfuric acid at 300°C reacts with tantalum at the rate of 342 mils/year.

The conclusion was: "Failure most probably occurred on the basic platinum resistance thermometer due to sulfuric acid collection on the platinum wire. Ground tests should be conducted on a similar sensor in a synthetic Venusian atmospheric descent from the cloud region to the failure altitude. The synthetic atmosphere should contain the major trace components of the clouds and the gaseous atmosphere." This conclusion does not explain the observed anomalies of the NFR and the other probe anomalies.

The Soviet Venera Probes: Differences from Pioneer Venus

Reports in the Soviet literature on the Venera probe missions do not address or discuss anomalies at the 12 km level. Soviet Venera and Vega Lander scientists, Victor Kerzhanovich and Vyacheslav Linkin, were asked if any anomalous behavior occurred at 12 km and they replied there was none (Seiff report to workshop).

A photograph and a drawing of the common configuration of the Venera and Vega Landers are shown in figure 4. Although the drawing is not very clear, there were many external instruments on the Venera probes shown in fig. 4(b), and titanium was used liberally. The central pressure vessel is an 82 cm diameter titanium sphere. It is encased in 11-cm thick exterior insulation (called KSBI), which apparently is a frangible material because it was enclosed within a retaining shell of thin titanium. Ahead of the pressure vessel is a toroidal ring (the bottom half is also apparently made of sheet titanium) to absorb the landing shock at a touchdown velocity of 8 m/sec. This is supported from the pressure vessel on ~16 tubular struts made of asbestos textolite (believed to be an asbestos-fiber-reinforced polymer). This is the same material used as a heat shield with maximum thickness 2.65 cm on the 2.4 m diameter outer sphere that encloses the Lander during hypersonic entry. Numerous external instruments and equipment are attached to the landing ring and its struts. It is not clear whether there were exposed wires or harness outside the pressure vessel, or whether these were protected within conduit, for example. Above the pressure vessel is a large drag ring to slow the descent of the capsule, and, above this, the parachute compartment and telemetry antenna. Two key instruments, the gas chromatograph and mass spectrometer are mounted outside the pressure vessel below the parachute canister. There are also four thin titanium blades (not identified in the picture) to damp rotational motion. No information is available on the nature of the insulation in the exterior electrical harness.

The Venera Landers have reported measurements down to the planet surface from the external sensors, including temperature sensors. Therefore, it appears that the Pioneer Venus anomalies are attributable to or associated with particular design features of the Probes or instruments.

Possible Atmospheric Effects

Over the years since encounter, a few atmospheric mechanisms have been suggested as possibly responsible for the anomalies, including electrostatic charging of the descending probes and subsequent discharges to the atmosphere. Chemical reactions of probe materials (notably titanium) with the atmosphere have also been discussed. Workshop science participants were invited to study these (and other) possibilities and to report their ideas and findings. Included are brief summaries of the phenomena proposed and investigated. More complete reports of these studies are published in volume 2.

Electrostatic Effects (W. Borucki)

The charging of aerosols in the atmosphere of Venus and the electrical conductivity of the atmosphere were calculated by Borucki et al. (ref. 20). Their calculations showed each of the three observed particle size distributions (ref. 21) to be charged. Although this model is not confirmed by observations, if these particles are indeed charged, the probes would have become charged by interactions with the particles, just as aircraft often experience charging currents of 250 microamps and, if unprotected by discharge wicks, become charged to voltages in excess of 500,000 volts (ref. 22). The probes would then retain the charge until it leaked away or until a situation arose that would trigger spark discharges. The interplay between the size distributions make it difficult to predict the polarity and magnitude of the charge that would be left on the spacecraft as it exited from the bottom of the aerosol layer that extends below the cloud bottoms to 30 km altitude.

The electric field around the probe cannot exceed the dielectric strength of the atmosphere. At 30 km altitude, the dielectric strength of the atmosphere is approximately 300 kV/cm. For a 0.75 m diameter sphere, up to 250 joules of electrical energy stored on the probe would produce such a field. Because of the booms protruding from the spacecraft, it is likely that the stored energy to create a discharge is much lower. The actual energy stored depends on the detailed interactions of the probes with the cloud particles.

Once the entry probes descend below the bottom of the aerosol layer at 30 km, no new charge is collected and ions produced by galactic cosmic rays begin to neutralize the charge that was collected with a time constant inversely proportion to the conductivity of the atmosphere. Based on the conductivity curve for the Venusian atmosphere given by Borucki et al. (ref. 20), the relaxation time is somewhat greater than 15 min at an altitude of 30 km and increases rapidly with pressure, reaching a value of 2.7 hr at 12 km. Because the probes descend to the 12 km level in about 25 min, only a fraction of the charge present at 30 km can leak away during the descent.

As the probes descend, increasing pressure might be expected to increase the dielectric strength of the gas and make spark discharges more difficult. However, the dependence of dielectric strength on density is seldom linear above a few bars for most gases, and typically there exists a critical pressure where dielectric strength falls precipitously for nonuniform fields (refs. 23 and 24). For air, the critical pressure at 286 K is 10 bars; at 373 K, it is 21 bars. Consequently it is possible that the entry probes became charged during their passage through the clouds and haze and did not have time to be fully neutralized by ions in the atmosphere before they descended to the critical pressure, where spark breakdown occurred. The highest electric fields occur on the sharpest protrusions from the spacecraft and it is at these protrusions that sparking is most likely. Because the temperature and net flux radiometer sensors are small diameter projections, they are the most likely locations for electrical discharges. It is possible that electrical sparks not only damaged the instrumentation directly, but could also have ignited local fires that then damaged the instrument wires, the wire insulation, or the cables that carried the signals and the power. Energetic electrical discharges are a well known source of fires, and if materials flammable in CO_2 are nearby, they could have been set afire. That the Soviet probes did not experience anomalous behavior at 12.5 km from this or other mechanisms could be explained by the absence of flammable or vulnerable components near discharge sites.

Relevant to chemical reactions, Gaydon and Wolfhard (ref. 25) state that "... it is interesting to note that zirconium, magnesium, and titanium are easily ignited in pure CO_2." Although it is known that many metals burn in CO_2 at room temperature and pressure, very little data is available for what happens at the much higher temperatures and pressures (650 K and 47 bars) experienced by the probes near 10 km altitude (ref. 7). However, for the flames commonly studied in the laboratory, it is found that temperatures rise with increasing pressure and the flammability limits become wider (ignition becomes easier).

These observations lead to the following scenario: (1) The probes acquire charge during passage through the clouds. (2) As they emerge and descend below the clouds and aerosol layer, the charge tends to be neutralized by atmospheric ions, but with a time constant longer than the descent time, leaving the probes appreciably charged at 12 km. (3) At 12 km, the atmosphere attains the critical pressure and temperature at which the breakdown potential drops precipitously. (4) Energetic sparks occur at the external sensors and wiring. (5) The sparks ignite fires on the probe materials that are flammable in CO_2, which include titanium.

Conductive Condensates in the Deep Atmosphere (A. Seiff)

The similarity of the ASI temperature anomaly to the T_1 shorting response in the clouds suggests the possibility that a conductive material, perhaps a metal, condensed on the sensor in the deep atmosphere. Because both T_2 and T_1 were affected, something was different about the presumed deep atmosphere condensate compared to the cloud condensate (sulfuric acid). Perhaps the difference was a greater mass deposited, leading to a longer conducting path from an exposed T_2 lead juncture to the uncoated region of the frame.

There are two independent observations that bear on this possibility of a conductive condensate. One is the observation by the Magellan microwave radiometer of sharply lower radar emissivity and increased conductivity of the planet surface at elevations above 5 km. This change was discussed by Pettingill et al. (ref. 26) and is illustrated in figure 5 (ref. 27). The high-altitude regions are highly radar reflective, as is typical of conductors. At these levels, surface condensation or deposition of a substance with high conductivity would produce this effect. There is no proven explanation for the observed anomalous reflectivity, but it is consistent with a constituent vaporized from the surface that condenses on the mountain tops (and the probe).

The second independent observation is that no aerosols were seen at these levels by the nephelometer, except at 6 km on the nightside (ref. 8). It is difficult to imagine a condensate that does not form aerosols, but condenses on a large object (the probe) only slightly cooler than the atmosphere. This could imply a very small population of nuclei on which aerosols could form. Thus, if condensation occurs, it is only on the mountain tops and the probe surface.

Atmospheric temperature data indicate that the layer between 13–20 km is stable (ref. 7). Large probe descent velocities (derived from the pressure data) show oscillations with altitude in this layer, implying the presence of waves and consistent with the finding of stability from temperature data. In the lowest 6 km, the atmosphere was found, in data acquired by Vyacheslav Linkin and colleagues with the Soviet Vega 2 Lander (ref. 28), to be unstable and therefore convective. Under these conditions, species vaporized from the surface are convected and mixed upward to the level of the stable layer where the upflow is capped, trapping the convected species. Is there a connection between this and the probe anomalies?

Lewis (ref. 29) expected mercury to be vaporized at surface temperature and transported upward to form clouds, but none was seen by the Pioneer Venus probes. The large probe neutral mass spectrometer did not find mercury, but placed an upper limit of 5 ppm on its mole fraction. In a private communication, Thomas Donahue remarked to the first author that mercury vapor could pass through the inlet and condense on the cold instrument walls and go undetected (ref. 30).

In sufficient concentration, mercury vapor would condense on the probe and the exposed sensors below 13 km and short the free-wire T_1 sensor to the frame. It would not short the T_2 sensor unless the sensing element-lead junctures were exposed (a distinct possibility). And it would not easily explain the NFR temperature sensor anomaly because this sensor wire was insulated and behind a titanium shield. But fine mercury droplets coating the NFR window would reflect and block incident radiation, causing readings to fall abruptly, as observed. Hence, a conductive condensate could explain a number of the things observed.

From the phase diagram, at a partial pressure of 1 atm, mercury condenses at 630 K. This partial pressure corresponds to a 0.025 mole fraction of mercury at the 40 bar level, which is 50 times higher than Lewis' suggested upper limit of 0.0005. At this lower concentration, mercury condensation would occur at an altitude of 32.5 km where no cloud was seen. The absence of a mercury cloud at 32.5 km could be a consequence of the mercury being trapped in the convective layer below 13 km. But condensation on the mountain tops is prohibited by surface temperatures greater than the vaporization temperature at this partial pressure.

There are other candidate, conductive substances including potassium and cadmium. Potassium is liquid above 336.4 K, and has a vapor pressure of 1.7 mb at 635 K, corresponding to a mole fraction of 45 ppm. It is not ruled out by mass spectrometer data because its isotope masses overlap those of argon, from which it would be indistinguishable. Cadmium is liquid above 594 K, with a vapor pressure of ~0.7 mb at 635 K, and a mole fraction ~20 ppm in equilibrium with the liquid. Both cadmium and potassium are commonly present in Earth's volcanic gases in combined forms (ref. 31).

Condensation of a conductive species does not appear to be a likely cause of the probe anomalies. Contrary indications are: (1) lack of aerosols below 13 km;. (2) inadequate mercury abundance; (3) chemical reactivity of conducting species, discussed below; (4) involvement of the T_2 sensor in the anomaly; and (5) involvement of the NFR temperature sensor.

Equilibrium Chemistry in the Deep Atmosphere (R. Craig)

Equilibrium chemistry at and below 17 km was investigated to: (1) study the reactions of titanium with CO_2 as an oxidizing agent, i.e., to explore the possibility of a burning probe, and (2) study the fate of possible conducting condensates in an atmosphere having the bulk and trace species composition of reference 32.

The metals chosen for initial consideration were titanium, potassium, iron, and magnesium. Titantium was of interest because it was the material used to construct the large probe's aerofaring and spin vanes, the pressure vessels of all four probes, and parts of the NFR. The latter three metals were found in surface composition measurements by Veneras 13 and 14 (ref. 33). It was assumed that the metals could be present in the atmosphere, introduced as dust or as volatile compounds (e.g., chlorides) or as vapors that could reach the top of the convective layer.

The effects of introducing from 50 to 1000 ppm of these species on the equilibrium composition of the deep atmosphere were interesting and will be found in the elaboration of these results in volume 2. Here, only those results that bear on possible relationships to the anomalies are summarized.

At equilibrium, the metal atoms were found to be entirely consumed in reactions and yielded solid products: TiO_2; Fe_3O_4, FeS_2, and FeS (depending on the initial iron concentration); K_2SO_4, K_2CO_3, and KCl; and $MgCO_3$. Metallic titanium would indeed burn in the deep atmosphere of Venus if it were not protected by an oxide layer on the surface (similar to the layer which protects aluminum against burning in Earth's atmosphere).

The calculations further indicate that gas phase metal atoms are not present in chemical equilibrium at 13 km over Venus, but are replaced by the solid carbonates, sulfates, chlorides, and oxides. The oxygen in these compounds is provided by CO_2 (the oxidizing agent), and the sulfur by the 150 ppm of SO_2 in the atmospheric model.

There is a marked influence of the metals on the other trace species. While the levels of H_2O and hydrogen fluoride are relatively unaffected, the levels of SO_2 decrease and CO and H_2 are increased in the presence of trace quantities of metals. Graphite occurs with titanium, as CO_2 molecules are fully reduced to carbon. COS and H_2S are increased with titanium, potassium, and magnesium, but decreased slightly with iron. The HCl concentration is unaffected with titanium, iron, and magnesium present; but, with potassium in the atmosphere, HCl is depleted and the chlorine compound at equilibrium is KCl. Trace amounts of CH_4 occur with titanium, iron, and magnesium. Other species than those plotted were calculated, but were present at very minor concentrations (1 ppb or less).

The metals have interesting effects on the chemistry of the other trace species, which could explain deviations of the composition from equilibrium composition calculated in the absence of metal atoms. See volume 2 for further discussion.

Report of the Engineering Panel (D. Juergens)

The ASI temperature data from external temperature sensors on all four probes failed at nearly the same time that data from other sensors located on the exterior of the spacecraft failed. The scientific data from internal sensors continued without anomaly throughout descent. The ASI pressure sensors and accelerometers provided turbulence data along with the pressure and atmospheric density profiles. The last reported exterior temperature of the atmosphere (~640 K all four probes) is nearly identical to the eutectic temperature of 60/40 Sn/Pb solder. However, the Hughes Aircraft Company engineers were positive that all exterior harness connectors were crimped and not soldered. The instrument temperatures inside all four probes were below 300 K at the time of failure. The project members and others have proposed that the failures may have been due to electrical interaction with the atmosphere. However, these external sensor failures have not been reported on any of the Soviet Venera missions.

During the workshop, it was reported that the probes were never exposed to high-temperature system-level tests because of the cost of testing. A test of some sensors at high pressures, but not high temperatures, was performed in a CO_2 and dry nitrogen environment.

The engineering panel found that almost all of the reported anomalies could be explained by a breakdown of the external insulation, which reduced the resistance between conductors to kilohm levels. It is likely that the kapton insulation was chemically altered by some means (caught on fire), which resulted in a breakdown of the interwire impedance.

Probes developed for future missions in the lower atmosphere of Venus should be tested in a simulated atmosphere of CO_2 at simultaneously high temperatures *and* high pressures simulating Venus surface conditions.

A test of materials should be performed using the Pioneer Venus harness materials in CO_2 heated to 600–700 K at pressures of 30–50 bars to evaluate the cable insulation resistance and chemical tolerance of the harness to the Venus deep atmosphere environment.

Recommended Laboratory Testing (L. Sromovsky)

External cabling between sensor assemblies and the probe pressure vessels were provided by Hughes as part of the spacecraft. These cables consisted of bare leads covered with woven quartz or glass fiber sleeves (resin free) with individual leads wrapped in kapton. The leads were then lashed together to make complete cables. In some cases (e.g., the NFR net flux detector leads) pairs of kapton-wrapped leads were encased in a braided metal shield that was also wrapped in kapton before the leads were lashed together to make a complete cable assembly. Although kapton may be the best high-temperature polymer insulation, it is now known that kapton is not suitable for continuous operation at Venus surface temperatures.

Unfortunately, kapton-wrapped cable bundles were not tested under descent conditions prior to their use on the Pioneer Venus probes. They were tested in a nitrogen atmosphere and showed some degraded insulation between leads, presumably due to degradation of the kapton wrap and subsequent invasion of the fiberglass sleeves with conductive material. There is reason to expect that kapton degradation might be accelerated in a CO_2 atmosphere and perhaps at high pressures. Because the same type of cable construction was used on NFR and ASI connecting cables, it is natural to wonder if the nearly simultaneous anomalies of these two very different instruments might both be a consequence of the same cable degradation. This possibility cannot be ruled out by tests that have been conducted so far.

A new test to investigate the performance of the kapton-wrapped cables may unambiguously identify the origin of the Pioneer Venus anomalies. Such a test should include both shielded and unshielded cable elements, constructed in the same fashion as the flight cables, and possibly make use of spare flight cables if they are still available. The test should also include the bulkhead connector where connector pins might be exposed to material emitted by the degrading cable insulation. It may also be the case that the connector had a problem under descent conditions. It is not clear what testing was done on the bulkhead connector. In any case, it should be included as part of future tests.

The test should first be conducted in a pure CO_2 atmosphere, under the presumption that trace gases and sulfuric acid do not play a significant role. The amount of sulfuric acid that could be deposited on the cables as a result of cloud particle impact is extremely small; fixtures exposed to the direct gas stream outside the boundary layer would, on average, pick up only enough acid to make a layer approximately 10 μm thick (ref. 34). In the more protected locations of the external cabling, far less acid would be deposited. Furthermore, any acid deposited within the cloud layer would be evaporating as the probe descended below the clouds (an example of this effect is probably seen in the ASI T_1 sensors, which were temporarily perturbed in and just below the clouds, but returned to normal as temperatures increased).

In such a test, the temperature and pressure should follow the approximate time history of the probe descent, although by far the most relevant part of the test is the simulation of the approach to the 635 K point. During actual descent the bulkhead connector temperature will lag behind that of the atmosphere, and the cable will probably be hotter at the sensor connector than at the bulkhead connector. This temperature gradient could be an important factor in simulating the effect of cable degradation. If the hot part of the cable is generating vapor products near 635 K, these might condense on the colder connector and deposit a conducting layer of material between connector pins. But if the connector temperature is allowed to be as high as the cable, the condensation may not occur. Thus the thermal gradients during descent should probably also be simulated in the ground test.

Resistance between all leads and shields should be measured during the ground simulation of the descent conditions.

Addendum: Harness Tests Performed After the Workshop (A. Seiff)

Subsequent to the workshop, the recommended harness tests were started at Hughes Aircraft Company under the direction of Victor Rogers. The tests will be more fully reported elsewhere. The tests performed and some of the key results are summarized here.

The test facility was an existing 1-liter capacity chamber, 7.5 cm in inside diameter and 23 cm long, which was large enough to hold small harness samples. The chamber is capable of duplicating Venus' surface temperature and pressure with either CO_2 or N_2 as test gas. Specimens tested included harness material samples, harness specimens used in modern jet engines, and samples of harness cut from a damaged Pioneer Venus temperature sensor. The harness samples incorporated "field joints" of the type made at the time the instruments were installed outside the pressure vessels during probe assembly.

Preliminary tests showed that kapton, the material used to wrap the harness, was not discolored or severely degraded in CO_2 at 655 K and 55 bars for >30 min. However, when the Kynar shrink tubing used to enclose the Pioneer Venus field joints was tested, it was reduced to a blackened ash at temperatures above 600 K. A pungent gas, later deduced to be hydrogen fluoride, was present in the chamber after the test. The source of the gas is believed to be the Kynar, which is a fluorinated hydrocarbon polymer called polyvinylidene fluoride. (The manufacturer's literature states that Kynar decomposes—the polymer "unzips"—at temperatures above 600 K.) In tests of both the jet-engine harness and the Pioneer Venus temperature sensor harness, both including Kynar shrink tubing over field joints, insulation between the central conductors and the shielding dropped during test at temperatures just above 600 K from >100 megohms to <0.5 megohm (the minimum reading on the meter used). Insulation remained low for 2 to 3 min, then partially recovered, a behavior similar to that exhibited at 12 km on Venus in the Pioneer Venus temperature data (see fig. 3). Tests showed that this insulation loss occurred in N_2 as well as CO_2 atmospheres. In all cases, the breakdown potential of the joints after test (voltage at which a dead short is indicated) was unacceptably low, 250 volts versus 10^3 to 10^4 volts expected.

Interestingly, the kapton film used to wrap the leads was charred after tests in which Kynar degradation had occurred, probably as a result of attack by released hydrofluoric acid. The stainless steel walls of the test chamber were also discolored and pitted, and a white crystalline residue was deposited on the walls. When samples of this residue were mixed into water, the solution was sufficiently acid that it etched aluminum. Details of the shorting process have not been determined, but the highly corrosive hydrogen fluoride gas released would easily penetrate the braided metal shielding and the woven fiberglass insulation within the field joints, attack them and the lead wire, and leave deposits. The high-carbon-content ash left after decomposition of the Kynar polymer could also have infiltrated the fiberglass and contributed to the observed loss of insulation resistance.

From a search through old records, it was found that Kynar shrink tubing was not in the joint specification at the time of the final design review. It was added sometime later, possibly during final integration on the factory floor. Problems were encountered in "dressing" the joints because of poor accessibility. Kapton provided a solution to these problems. Brief high-temperature tests were conducted to qualify this material for use. From the tests, it was concluded that the kapton degraded, but did not impair insulation resistance. It was subsequently used on connectors for the temperature sensors, the net flux radiometers, the microswitches indicating sensor deployment, and the nephelometer window heater (which apparently was not seriously affected by kilohm level shorts).

The more recent tests strongly indicate that the decomposition of the Kynar shrink tubing was the central cause of the Pioneer Venus electrical anomalies.

Disposition of "Unexplained Anomalies" in Table 2

All of the anomalies can now be accounted for. In table 2, items 1, 3, and 4 were satisfactorily explained at the outset. Items 2, 5, 6, 7, 8, and 9 are explained by degraded insulation at external field joints. (Prior to the workshop, item 2 was mistakenly attributed to switch housing collapse.) Items 10 and 11 were not abnormalities, but were within the usual expected limits of digital data. Therefore, there are no remaining unexplained anomalies.

Summary and Recommendations

The electrical anomalies experienced by all four Pioneer Venus Probes, starting between 12 and 13 km above the surface, resulted in a partial loss of science data below that altitude. Prior to late 1993, the cause of these anomalies had never been explained or understood. A workshop held at Ames Research Center September 28–29, 1993, brought together principal investigators and instrument engineers of affected experiments, spacecraft designers, project office personnel, and independent scientists in an attempt to identify the cause of the anomalies. Objective evidence was reviewed, and possible causes were analyzed.

The review showed that not all of the numerous listed anomalies were unexplained. For those that were unexplained, two areas of possible cause were considered: atmospheric phenomena and hardware failures. Atmospheric phenomena considered included: (1) Chemical interactions of atmospheric constituents with the probe and sensors, such as reactions of residual H_2SO_4 from the clouds with harness or sensor materials, or CO_2 oxidation of titanium parts and/or polymers. (2) Condensation of conductive vapors on the external sensors in the deep atmosphere, leading to shorted electrical circuits. (3) Probe charging followed by electrical breakdown of the atmosphere, leading to sparks that could possibly ignite probe external fires. None of these could be dismissed a priori.

Of the hardware failures considered, the one identified as most likely to account for the anomalies was the insulation breakdown of the external harness, due to, for example, chemical interaction with the high pressure and temperature CO_2 atmosphere after exposure to the sulfuric acid clouds. Laboratory testing up to the time of the workshop did not conclusively rule this out.

The workshop reached the conclusion that the anomalies experienced by the probes in the deep atmosphere can be prevented on future Venus probes through design changes and tests to verify design effectiveness.

It was recommended that:

1. Additional laboratory tests be initiated to critically evaluate harness failure mechanisms. Pioneer Venus probe harness and external sensors (where available) should be tested in CO_2 at pressures and temperatures encountered at and below the anomaly level.

2. Greater emphasis should be placed on full simulation testing of probe external components in the development of future Venus probes.

3. Atmospheric mechanisms described herein be further evaluated by means of laboratory and theoretical research.

Subsequent to the workshop, recommended testing (item 1 above) was started and revealed the cause of the major anomalies to be insulation breakdown of the external harness due to the presence of an unqualified material. Although more research is needed to clarify and document the processes it appears that all of the anomalies have been explained. Furthermore, some of the atmospheric phenomena studied could be openings to important atmospheric research.

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Table 1. Anomalies experienced by the probes

Anomaly	Probe			
	Large	North	Day	Night
Temperature sensors apparently failed	X	X	X	X
Changes and spikes in pressure data	X	X	X	X
Apparent failure of net flux radiometer fluxplate temperature sensors		X	X	X
Abrupt changes and spikes in data from net flux radiometer		X	X	X
Change in the indicated deployment status of the atmosphere structure temperature sensor and net flux radiometer booms		X	X	X
Erratic data from two thermocouples embedded in the heat shield		X	X	X
Erratic data from a thermistor measuring junction temperature of the heat-shield thermocouples		X	X	X
Slight variation of current and voltage levels in the power bus		X	X	X
Slight offsets or jumps in the values for temperatures of the forward and aft shelves and the internal pressure		X	X	X
Abrupt changes in cloud particle size laser alignment monitor	X	NA	NA	NA
Decrease in the intensity of the beam returned to the cloud-particle-size spectrometer	X	NA	NA	NA
Steady increase in flux readings of the infrared radiometer	X	NA	NA	NA
Noise in the data from the infrared radiometer	X	NA	NA	NA
Spikes in the data monitoring the ion pump current of the mass spectrometer analyzer	X	NA	NA	NA
Abrupt decrease of current in the power bus	X	NA	NA	NA
Jumps in the receiver (transponder) static phase error	X	NA	NA	NA
Spikes in the receiver automatic gain control	X	NA	NA	NA
Spurious reading from thermocouples that had been dropped from the probe in its heat shield	X	NA	NA	NA

Table 2. Anomalies reported in NASA TM-84301

Anomalous event	Possible or probable cause
1. Pressure sensor offset jumps	Bursting of low range sensor diaphragms
2. Small probe booms restowed	Microswitch failures at 640 K, 40 b
3. Sudden decrease in large probe bus current	LIR window heater failed
4. Large probe infrared radiometer measured flux step change	LIR window heater failed
5. Discontinuous drop in ASI temperatures	Unexplained
6. NFR net flux data → zero	Unexplained
7. NFR resistance thermometer temperature discontinuities	Unexplained
8. Small probe heat shield thermocouples cold junction temperature dropped	Unexplained
9. Large probe thermocouple leads, cut by cable cutter, read 0.2 mv signals	Unexplained
10. Pressure vessel internal pressure and temperature showed small step increases	Unexplained
11. Large probe communication electronics showed a shift in static phase error and receiver AGC	Unexplained

Table 3. Conditions at ASI T sensor breakdown

	GRT,[a] sec	GRT, hr:min	T_{crit}, K	p_{crit}, b	LVT,[b] hr	Lat,[c] deg
Large probe	69,995	19:26.5	627.2	37.75	7.63	4.4
Small probe 1	69,950	19:25.9	640.2	40.05	3.58	59.3
Small probe 2	70,171	19:29.4	639.9	40.13	6.77	–31.2
Small probe 3	70,259	19:31.0	633.3	36.32	0.12	–28.7

[a]Ground received time.
[b]Local Venus time.
[c]Latitude.

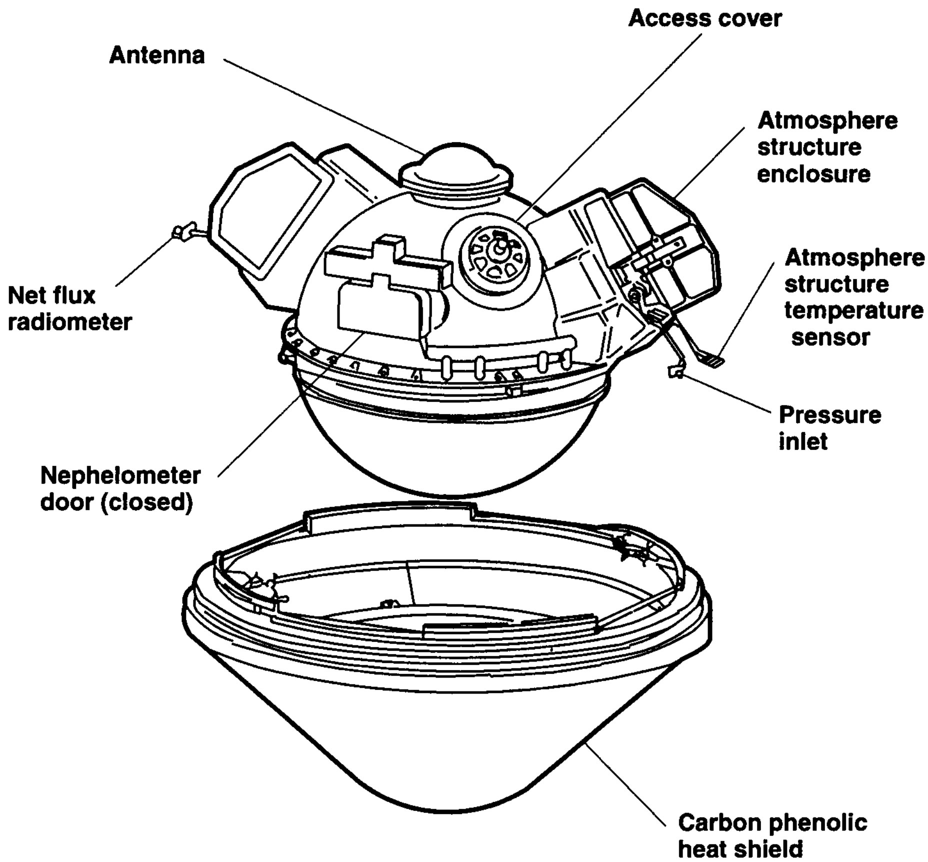

Figure 1. Descent configurations of the Pioneer Venus probes. (a) Small probe.

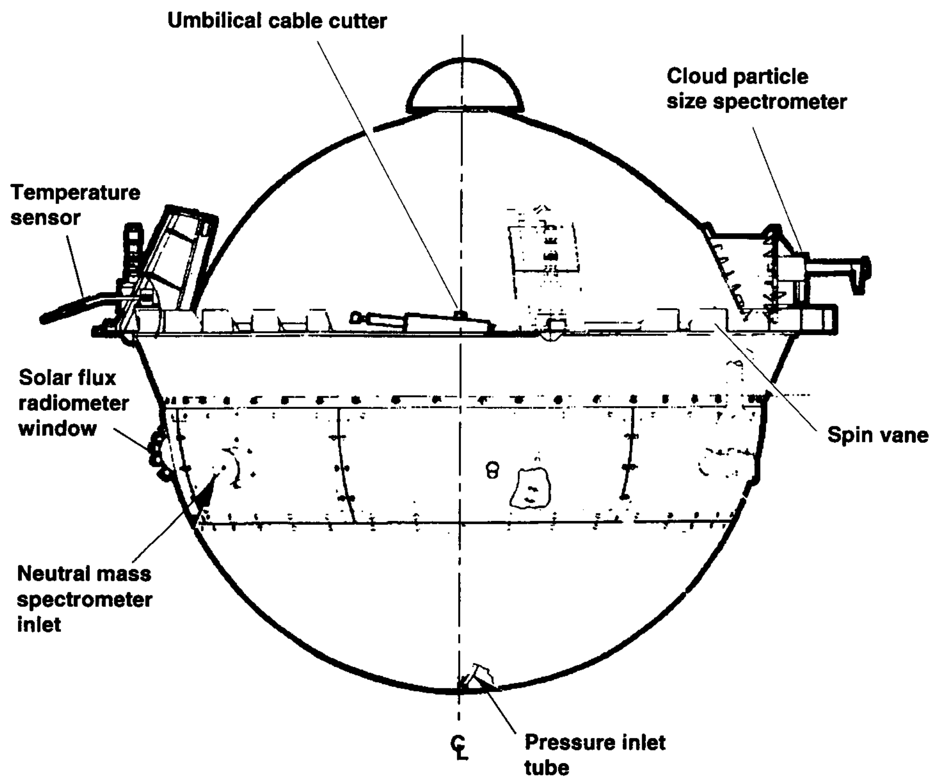

Figure 1. Concluded. (b) Large probe.

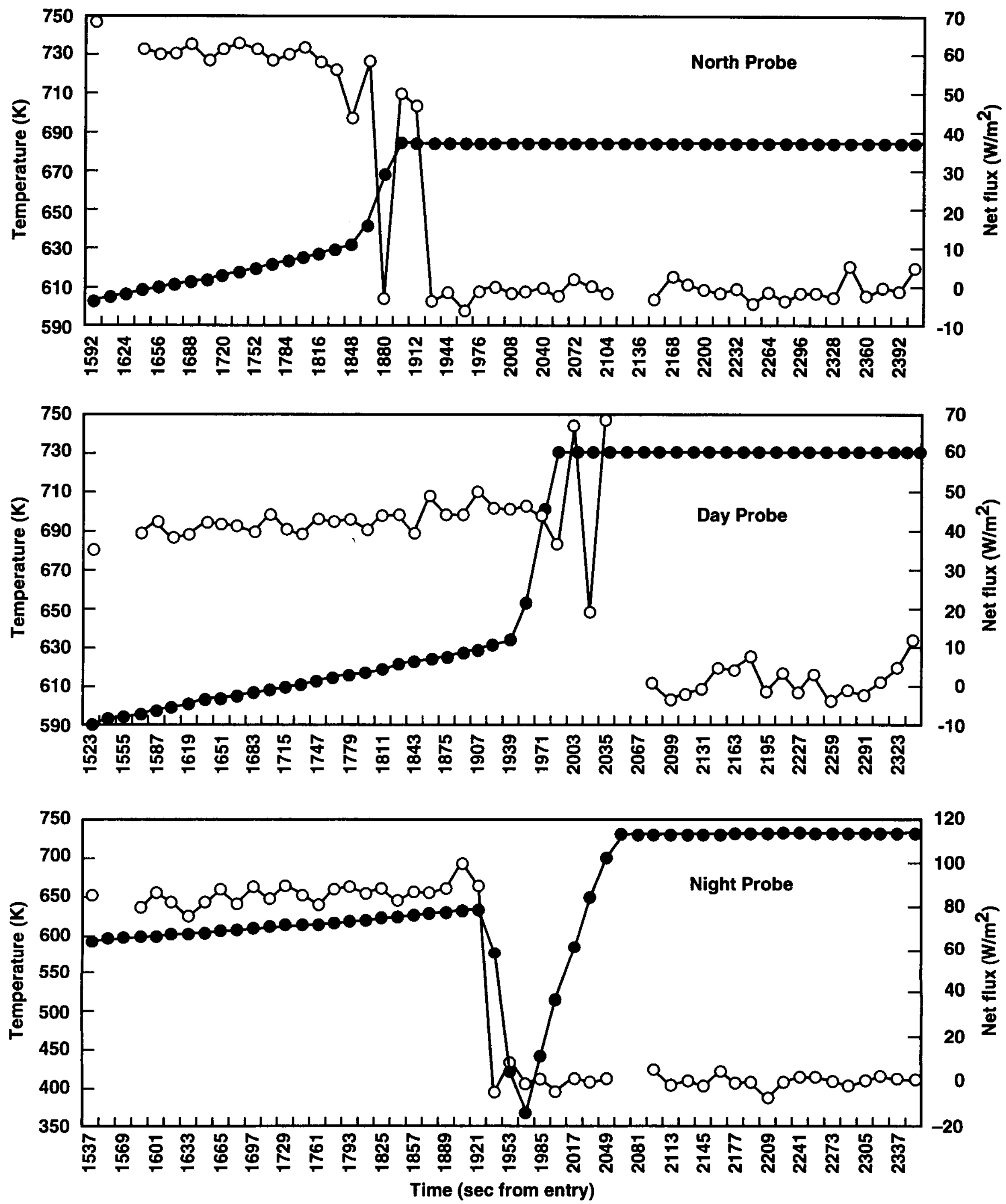

Figure 2. Data from the net flux radiometer late in the descent of the three small probes. Open symbols are net fluxes; filled symbols, atmospheric temperatures.

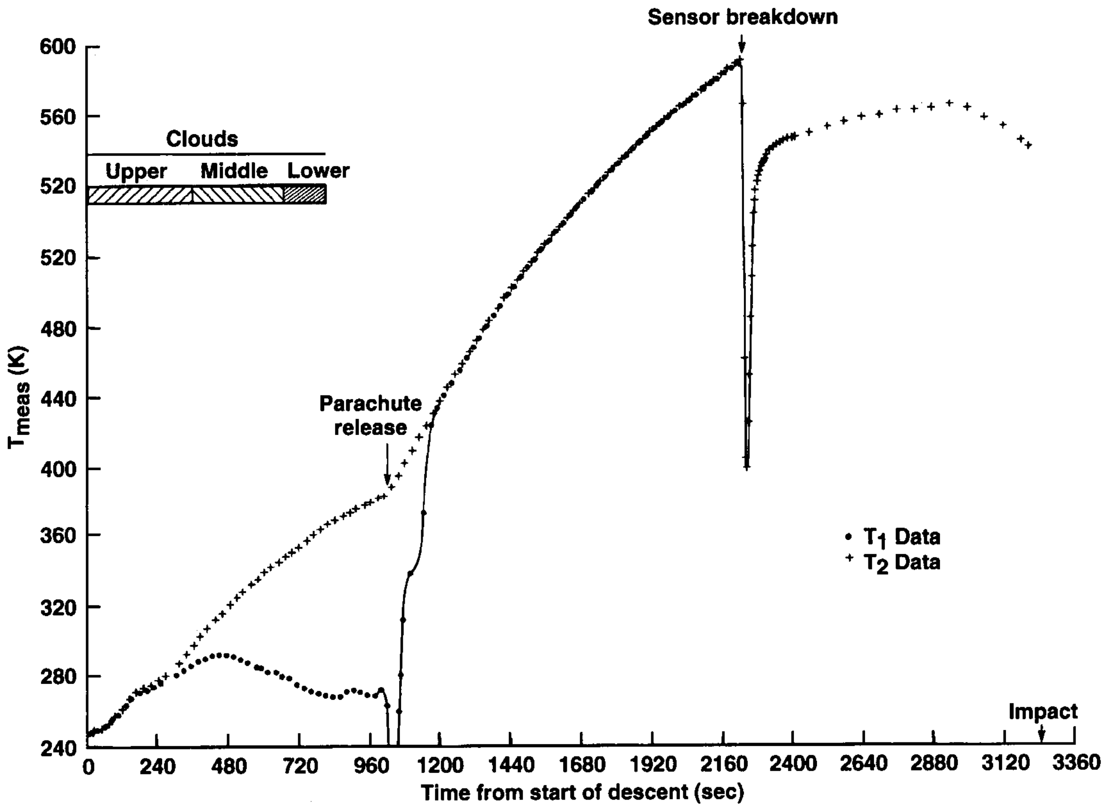

Figure 3. Atmosphere structure instrument temperature sensor breakdowns. (a) Large probe.

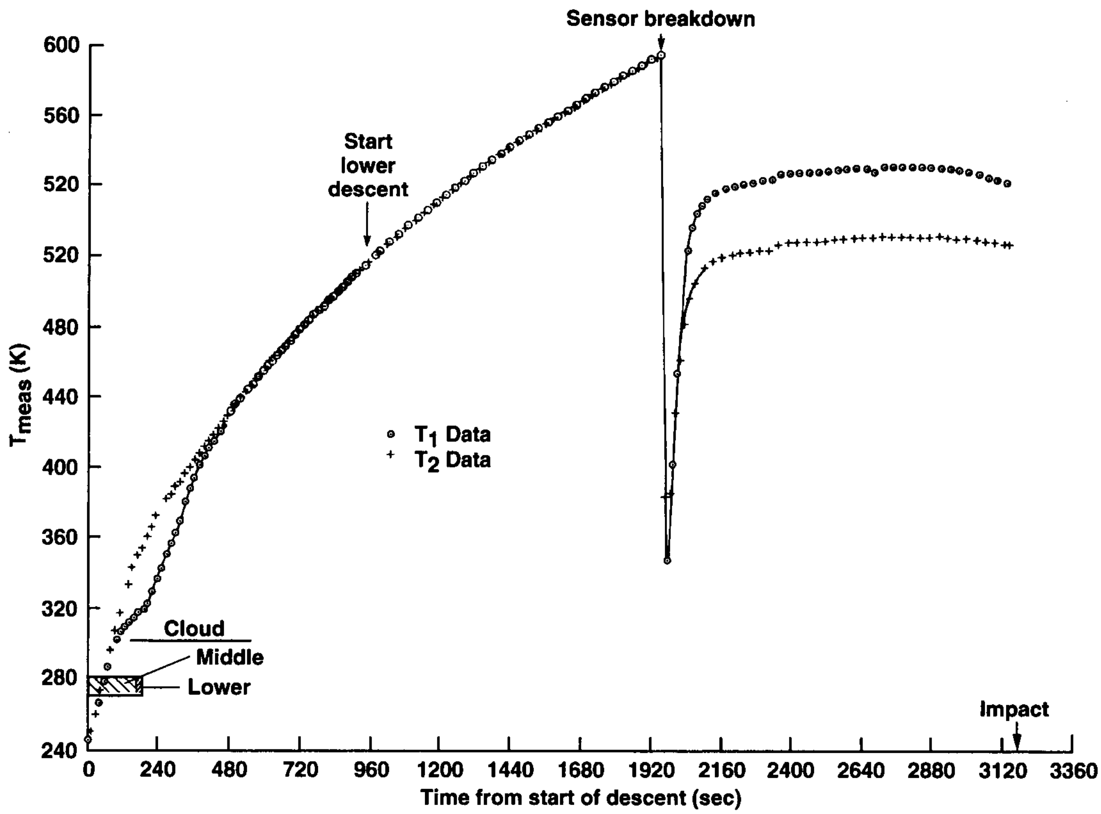

Figure 3. Concluded. (b) North probe.

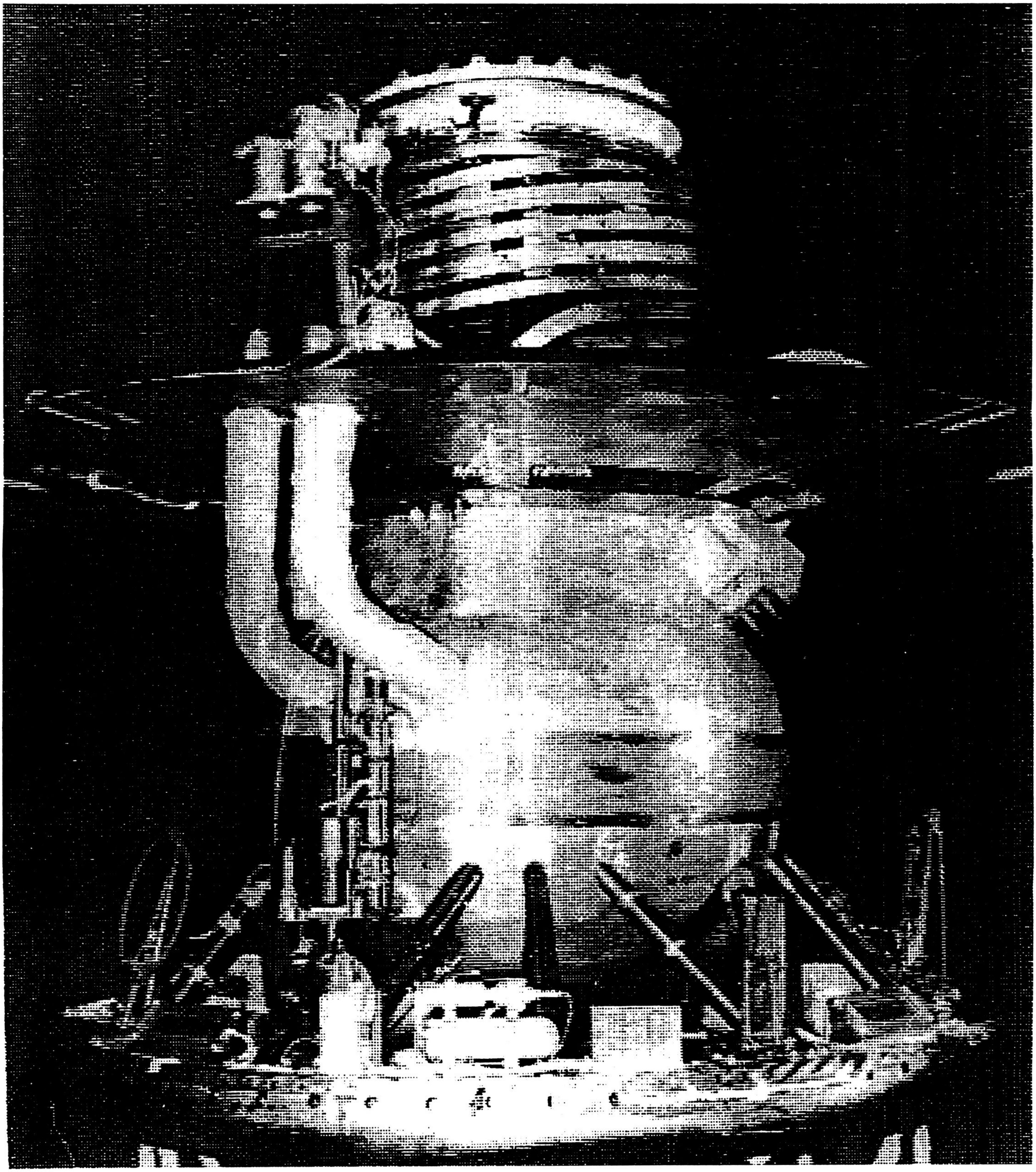

Figure 4. Soviet Venera Lander. (a) Photograph.

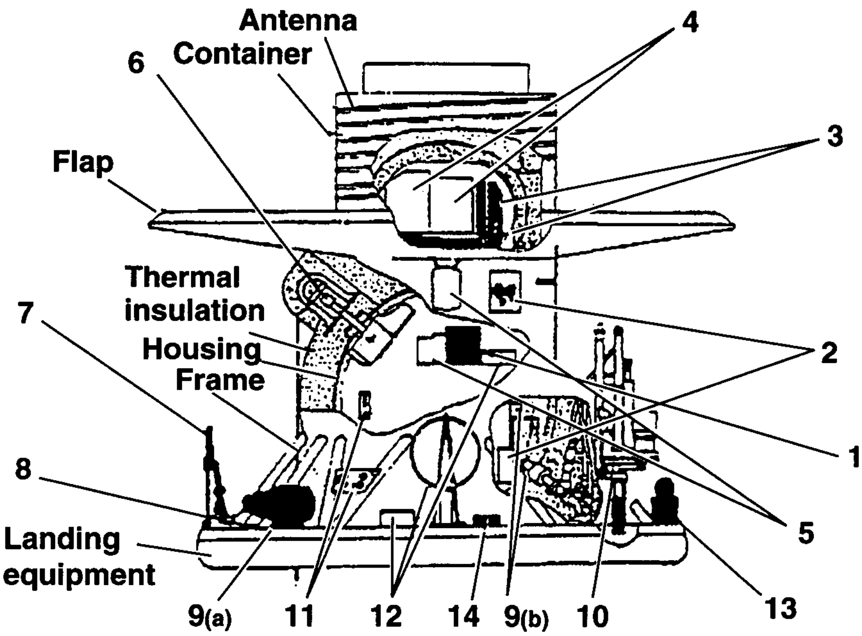

Figure 4. Concluded. (b) Instrument locations; (1) accelerometer, (2) particle size spectrometers, (3) mass spectrometer, (4) gas chromatograph (atmosphere and particles), (5) solar spectrometer photometer, (6) camera (used after landing), (7) soil mechanical properties and electrical conductivity instrument, (8) oxygen detector (9) (a) and (b) x-ray fluorescence spectrometers (soil chemical analysis), (10) soil sampling mechanism for x-ray fluorescence analysis, (11) descent pressure and temperature sensors, (12) microwave spectrometer, (13) hydrometer (measured atmospheric water content during descent), and (14) solar radiometer (measured luminosity during descent).

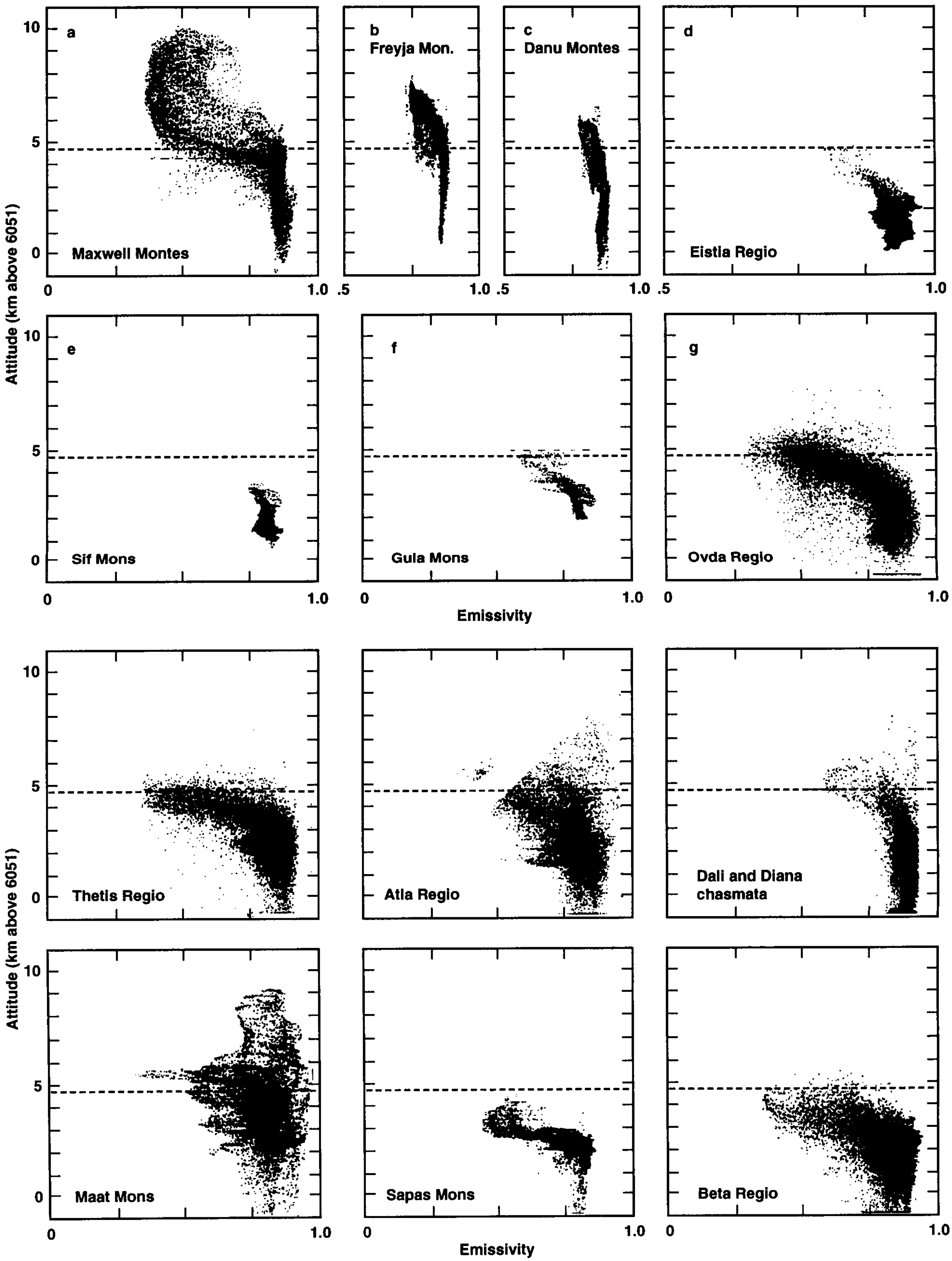

Figure 5. Magellan data on the radio emissivity of Venus' surface as a function of altitude (ref. 27).

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13. ABSTRACT *(Maximum 200 words)*

A workshop was convened at Ames Research Center on September 28 and 29, 1993, to address the unexplained electrical anomalies experienced in December 1978 by the four Pioneer Venus probes below a Venus altitude of 12.5 km. These anomalies caused the loss of valuable data in the deep atmosphere, and, if their cause were to remain unexplained, could reoccur on future Venus missions. The workshop participants reviewed the evidence and studied all identified mechanisms that could consistently account for all observed anomalies. Both hardware problems and atmospheric interactions were considered. Based on a workshop recommendation, subsequent testing identified the cause as being an insulation failure of the external harness. All anomalous events are now explained.

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