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PIONEER VENUS AND GALILEO ENTRY PROBE HERITAGE

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ABSTRACT

Beginning in the late 1960s, NASA began planning for its first program to explore Venus. Although planetary entry probes had been flown to Venus by the Soviets beginning in 1967, NASA had not previously flown this type of mission. The Space and Communications Group of Hughes Aircraft Company, now owned by Boeing and called Boeing Satellite Systems, worked with NASA to perform initial studies that culminated with a contract for the Pioneer Venus program in early 1974. Pioneer Venus was an ambitious program that included four planetary entry probes, transported to Venus by a Multiprobe Bus, and a Venus Orbiter. This paper focuses on the engineering aspects of the probes and the challenges overcome in accommodating the various scientific instruments.

The second NASA planetary entry program was the Galileo Mission that began with initial studies in the early 1970s. This mission to Jupiter included both an Orbiter and a Probe. Although the Galileo Probe planetary entry program was begun as the Pioneer Venus probes were heading towards Venus, there were significant engineering differences between the Pioneer Venus probe designs and the Galileo Probe. These differences, dictated by a number of factors, are discussed. The paper concludes with a summary of lessons learned by Boeing and NASA in designing, manufacturing and ultimately flying the Venus and Jupiter planetary entry probes.

1. PIONEER VENUS INTRODUCTION

In June 1968, the National Aeronautics and Space Board recommended that a Venus mission be planned for the 1978 launch opportunity to study the atmosphere and clouds of Earth's nearest neighbor. Although various Russian spacecraft had previously explored Venus as part of the extensive Venera program, the US mission was to be the first NASA atmospheric entry mission to Venus. Hughes Space and Communications Company, since purchased by Boeing, began work on developing a design to support NASA's Venus exploration effort, called Pioneer Venus. Hughes, in conjunction with NASA's Ames Research Center (ARC) in Moffett Field, California, was awarded a study contract that produced a final report outlining the plans for conducting the Pioneer Venus mission.

The Hughes/NASA ARC report described a Pioneer Venus mission that included a Venus Orbiter, as well as a Venus Multiprobe Bus that was to carry three Small Probes and one Large Probe to a near-Venus release for entry and descent into the Venusian atmosphere. In June 1973, NASA ARC issued an RFP for the design and development of the Pioneer Venus spacecraft system. Hughes responded with a proposal and on February 4, 1974, was awarded the contract for the Pioneer Venus program. Although the Pioneer Venus Orbiter as well as the Multiprobe Bus were challenging vehicles in their own right, this paper will focus on the design of the Pioneer Venus Large and Small Probes.

2. VENUS DESIGN CHALLENGES

The primary challenge in designing the probes was the harsh environments to which the probes would be subjected as they entered and descended into the Venus atmosphere. All four probes would be traveling at approximately 11.7 km/sec as they encountered the atmosphere, and would be subjected to deceleration in excess of 300 g's. During descent, the probes would pass through clouds of sulfuric acid and then experience a dramatic increase in temperature and pressure that would result in surface temperatures in excess of 450 °C and surface pressures at roughly 100 Earth atmospheres. These harsh conditions drove the overall design of both probes to include a pressure vessel, to protect the science instruments and probe subsystems, and a deceleration module, to prevent entry heat loads from destroying the pressure vessel. Figs. 1 and 3 illustrate the major elements of the Large and Small Probes, respectively

Since neither the science instruments nor the probe subsystems could operate in the severe environment in the Venus atmosphere, the structural and thermal design of the probes was the first design hurdle.

3. PIONEER VENUS LARGE PROBE STRUCTURAL DESIGN

Early in the detailed design of the probes, the materials to be used for the spherical pressure vessels had to be selected. Several different metals were considered for

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the probe structure, before titanium was selected. It maintained its strength at the extremely high temperatures encountered during descent, at a modest thickness.

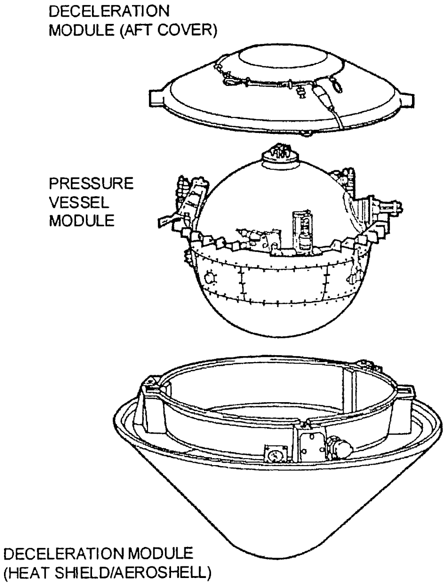

Fig. 1. Large Probe Major Elements

The Large Probe spherical pressure vessel was manufactured in three pieces, to aid access to the internal units, consisting of forward and aft dome-shaped sections, joined to a midsection element. These three sections were bolted together with a seal system consisting of O-rings, to prevent the internal nitrogen gas pressurized at 102 kPa from leaking out during transit between Earth and Venus. The seal system also included graphoil flat gaskets to prevent leakage of the Venusian atmosphere hot gases into the probe during descent. At a pressure vessel diameter of 78 cm, the two Large Probe sealing surfaces totaled nearly 5 meters. In order to allay the concerns that minute leaks in the seal system would have allowed the small nitrogen gas molecules to leak out during the long transit time between Earth and Venus, thus compromising the thermal design, a small nitrogen pressure bottle was flown. Although an internal vacuum with the pressure vessel was preferred by the thermal engineers, nitrogen gas was added late in the program to provide the science instruments with a backpressure and to prevent potential corona discharges within the probe that could damage the sensitive electronics within.

During the coast period of the mission, between separation from the Multiprobe Bus and atmospheric entry, the stored command sequence opened the bottle to increase the internal nitrogen pressure by 41 kPa. The Large Probe design is summarized in Table 1.

Table 1. Large Probe Design Summary

Total Mass	302 kg
Deceleration Module	109 kg
Pressure Vessel	193 kg
Diameter	
Aeroshell	142 cm
Pressure Vessel	78 cm
Battery	19 cell, AgZn, 40 A-h
Date Rate	128/256 bps
Pressure Design	
Penetrations	11
Windows	9 (8 sapphire, 1 diamond)
Science Instruments	7 total, 35 kg, 106 W
LAS	Atmospheric structures
LN	Nephelometer
LCPS	Cloud particle size spectrometer
LIR	Infrared radiometer
LNMS	Neutral mass spectrometer
LGC	Gas chromatograph
LSFR	Solar flux radiometer

4. PIONEER VENUS SMALL PROBE STRUCTURAL DESIGN

The Small Probe design was similar to the Large Probe design with several exceptions. Each of the Small Probes pressure vessels was manufactured in two hemispheres that were joined together with a system of O-rings and graphoil seals as on the Large Probe. After overheating in the Small Probe during thermal testing on a non-flight pressure vessel, with nitrogen used as the pressurant gas as on the Large Probe, thermal engineers determined that a high molecular weight gas was required to minimize heat transfer within the probe. Xenon was selected and demonstrated to maintain the desired thermal environment during intense thermal and pressure testing. Since the Small Probe gas volume was considerably less than that of the Large Probe and because the xenon atom was large compared to the nitrogen molecule, there was no requirement for a xenon pressure bottle to be flown on the Small Probes. Table 2 summarizes the Small Probe design.

The thermal environment within the probes was controlled by the use of multilayer thermal blankets, beryllium shelves, and careful attention to thermal isolation of components within the probe. The 2.5 cm thick thermal blankets were held in place against the probe walls by a system of thin titanium retainers.

Protection against the extreme heat generated during atmospheric entry was provided by the deceleration module that was attached to the forward end of the spherical pressure vessel. It consisted of a 45° half angle blunt cone, covered with a carbon phenolic material that ablated during atmospheric entry to maintain the probe science instruments and subsystems within their required operating temperatures. The major elements of the Small Probe are illustrated in Fig. 3.

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Table 2. Small Probe Design Summary

Total Mass	94 kg
Deceleration Module	33 kg
Pressure Vessel	61 kg
Diameter	
Aeroshell	76 cm
Pressure Vessel	47 cm
Battery	20 cell, AgZn, 11 A-h
Date Rate	64 / 16 bps
Pressure Design	
Penetrations	7
Windows	2 (sapphire)
Science Instruments	3 total, 5 kg, 10 W
SAS	Atmospheric structures
SN	Nephelometer
SNFR	Net flux radiometer

5. PIONEER VENUS PROBES MISSION DESCRIPTION

The difference in mission requirements for the Large and Small Probes drove the design of the pressure vessel/deceleration module integration scheme. Since the Large Probe contained more instruments than the Small Probe, all of which required either windows for viewing the atmosphere or inlets for sensing the atmosphere, it was necessary to extract the pressure vessel from the aeroshell and aft cover. The extraction sequence was accomplished by use of a mortar-fired pilot parachute that in turn pulled off the aft cover, allowing the main parachute to deploy. Once the main parachute stabilized the descent of the Large Probe, explosive bolts separated the aeroshell so that all instrument windows and inlets covered by the aeroshell were exposed to the Venusian atmosphere. The Large Probe remained attached to its main parachute to allow the instruments to thoroughly evaluate the cloud layer. After descent through the cloud layer, at approximately seventeen minutes after deployment, the parachute was released to allow the exposed pressure vessel to free fall to the Venusian surface. The Large Probe descent sequence is illustrated in Fig. 2.

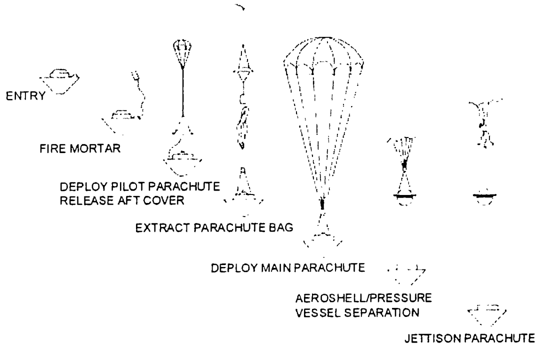

Fig. 2. Large Probe Descent Sequence

The Small Probe descent sequence was considerably simpler. The three instrument sensors were located above the Small Probe deceleration module, mounted in housings to protect them from the entry environment; thus it was not necessary to deploy the deceleration modules so that the Small Probes retained their aeroshells throughout descent to the surface. Fig. 3 illustrates the Small Probe major elements.

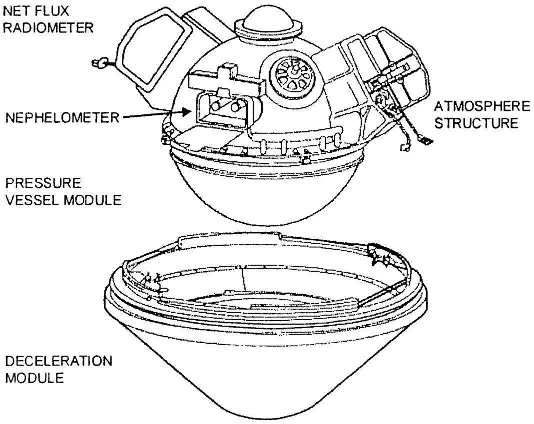

Fig. 3. Small Probe Major Elements

The Large and Small Probes all had a requirement to align with the local vertical for descent into the thick Venusian atmosphere. This descent orientation ensured that their carbon phenolic heat shields would properly ablate to protect the pressure vessel and its science payload. The Large Probe was separated from the Multiprobe Bus spinning at 15 rpm. This rate was slow enough to ensure proper alignment and uniform solar loading, at nearly two suns, over the entire probe during the coast period.

The three Small Probes were mounted equidistant about the periphery of the Multiprobe Bus. In order to target the three Small Probes to enter the Venusian atmosphere at widely spaced points relative to each other, the Multiprobe Bus was spun up to 48 rpm prior to the simultaneous, frisbee-like release of the Small Probes. Although required for the entry location dispersion, the Small Probe spin rate was too high to ensure proper heat shield alignment during entry. For this reason, at approximately 4 minutes prior to entry, a sequencer actuated a yo-yo weight system that deployed small masses at the end of cables. This change in probe momentum reduced the spin rate from 48 to 17 rpm to properly align the heat shields. Following despin, each yo-yo mass was self-jettisoned to prevent the cables and masses from interfering with other instrument deployments as the Small Probes descended.

Table 3 summarizes the Large and Small Probe performance at Venus on December 9, 1979. The probes

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mission began several weeks earlier, with separation of the Large Probe from the Multiprobe Bus on November 16 and simultaneous release of the Small Probes on November 20.

Several aspects of the Pioneer Venus probes' performance are worth noting. All three Small Probes descended at disparate locations, within minutes of each other, per the science requirements. The aerodynamic characteristics of the Large Probe were designed to be consistent with the descent rate of the Small Probes. Even though the Large Probe deployed two parachutes to extract the pressure vessel from the aeroshell, its descent time was quite similar to that of the three Small Probes. Finally, the day probe proved to be a hearty vehicle. Although not specifically designed to survive landing, it transmitted from the surface for over an hour. During that period, it returned basic engineering data before battery depletion and temperature increases above the electronics operating point caused the transmitter to cease operating.

Table 3. Pioneer Venus Probe Mission Events

Event	Large Probe	North Probe	Day Probe	Night Probe
	Time at spacecraft, GMT (HH:MM:SS)			
Coast timer timer-out	18:24:26	18:27:57	18:30:27	18:34:08
Telemetry initiation	18:29:27	18:32:55	18:35:27	18:39:08
Yo-yo despin release*	--	18:45:55	18:47:18	18:51:13
Entry (200 km)	18:45:32	18:49:40	18:52:18	18:56:13
Loss of signal (blackout)	18:45:52	18:49:58	18:52:40	18:56:27
Relock signal	18:46:55	18:50:55	18:53:46	18:57:48
Deploy pilot parachute	18:47:46	--	--	--
Jettison main parachute	19:03:28	--	--	--
Impact	19:39:53	19:42:40	19:47:59	19:52:05
Loss of signal	19:39:53	19:42:40	20:55:34	19:52:05
	Durations			
Descent time	00:54:21	00:53:00	00:55:41	00:55:52
Blackout time	00:01:03	00:00:57	00:01:06	00:01:21
Time on chute	00:17:56	--	--	--
Operating time on surface	None	None	01:07:35	None

Large Probe peak deceleration: 280 g's (entry angle = 34°)
Small Probe peak decelerations: 223 to 458 g's (entry angles 23° to 71°)
Large Probe impact velocity: 32 km/hr (8.9 m/sec)
Small Probe impact velocity: 36 km/hr (10 m/sec)
* Yo-yo release reduced spin rate from 48 to 17 rpm

6. PIONEER VENUS PROBES SUBSYSTEM DESCRIPTION

The general arrangement of the instruments and subsystems in the Large and Small Probes is shown in Figs. 4 and 5, respectively. Electrically, the Large and Small Probes were of similar designs. Silver zinc secondary batteries provided the power for all four probes, with varying cell counts and ampere-hour capacities as indicated in the overview charts. Power to all users within the probes was unregulated and switched directly from the battery to each of the probe subsystems and science instruments by the power interface unit (PIU). Each of the four probes required a squib driver unit (SDU). On the Large Probe, an extensive system of explosive bolts and cable cutters was required to separate the various elements and to deploy and jettison the parachutes. Pyrotechnic functions on the Small Probes included opening of the instrument doors and yo-yo weight activation, as described earlier.

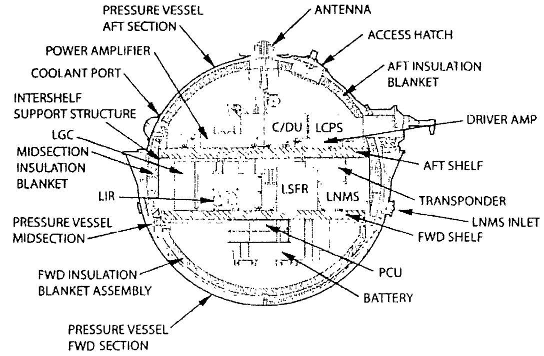

Fig. 4. Large Probe General Arrangement

Each probe contained identical command/data units (CDUs) that controlled and monitored the status of all probe subsystems and science instruments, provided data storage for science data generated during the short ionization blackout period, and formatted the science and engineering data for transmission directly to the NASA's 64 m S-band Deep Space Network (DSN) antennas. Each CDU provided multiple telemetry formats, tailored to the mission requirements. For the Large Probe, the blackout format operated at 128 bps, while the data rate for the normal descent format doubled to 256 bps. On the Small Probes, because there were fewer instruments generating data, the bit rates were scaled down to 64 bps during the blackout format and upper descent format and then reduced to 16 bps during the lower descent format.

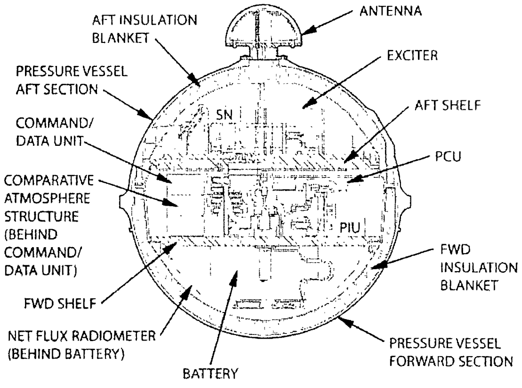

Fig. 5. Small Probe General Arrangement

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The communications subsystem design differed between the Large Probe and Small Probes. The Large Probe subsystem consisted of four summed 10 watt solid state power amplifiers, producing a total transmitted power of 40 watts at S-band. The Large Probe also included a transponder, consisting of an exciter and receiver, in order to implement the two-way Doppler tracking function. There was no RF command capability on the Large Probe. The communications subsystem on the Small Probes was considerably simpler. It consisted of a single 10 watt, S-band, solid state amplifier, an exciter, and stable oscillator to allow one-way Doppler measurements of each Small Probe.

7. PIONEER VENUS LARGE PROBE SCIENCE INSTRUMENT ACCOMMODATION

Accommodation of the science instruments on each of the two probe designs differed as well. The Large Probe supported seven science instruments, as indicated in Table 1. In total, 11 pressure vessel penetrations in the Large Probe were required for the various science instruments to complete their observations of the Venusian atmosphere. These penetrations varied from a pressure inlet for the gas chromatograph (LGC) to a complex window for the infrared radiometer (LIR). Each penetration type required precise engineering and substantial testing to verify that the design could withstand the tremendous temperatures and pressures as the Large Probe descended to the surface.

A major design consideration for the windows was driven by the sulfuric acid cloud layer known to exist between 70 and 45 km. The science community was concerned that the visibility through the science instrument windows would be obscured by condensation from the clouds. Various design concepts were evaluated before a simple design was developed. Each window was electrically heated by a perimeter heater to effectively boil off the condensates. Although an elegant solution to the perceived problem, implementation of the window heaters proved to be a major design challenge.

Implementation of the infrared radiometer (LIR) window on the Large Probe, as shown in Fig. 6, proved to be quite a difficult matter. The saga began with a specification of the window material. Although all other windows in the Large and Small Probes were fabricated using sapphire glass, this material would not meet the LIR requirements. Other materials, with satisfactory optical properties, were unacceptable for flight since they could not stand up to the severe pressure and temperature environment. The instrument principal investigator as well as the probe window specialists finally concluded that natural diamond was the only possible window material. The next challenge was procurement of an uncut stone that would yield the proper size window. After an intense search conducted by New York's diamond merchants, two stones, weighing 31 and 200 carats respectively, were purchased to yield the prime and backup windows.

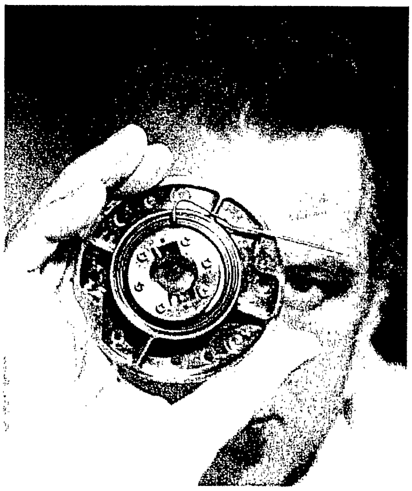

Fig. 6. LIR Window

One last challenge awaited the engineers designing this single most expensive component in the Large Probe. Whereas seals for all other probe windows were implemented using a brazing technique, this method would not properly seal the diamond window due to the hardness of the diamond. Experiments with other novel techniques proved unsatisfactory. Eventually the LIR window seal was achieved using a preloaded system consisting of a graphoil sealing surface with Anviloy and Inconel, that was demonstrated to maintain a leak-proof seal for the diamond window.

8. PIONEER VENUS SMALL PROBE SCIENCE INSTRUMENT ACCOMMODATION

The Small Probes, supporting only three science instruments, each required 7 penetrations for the science instruments. Although the penetration count was lower than that on the Large Probe, the complex aspect in accommodating the science instruments on the Small Probes proved to be the design of three instrument housing doors that opened at approximately 70 km above the surface. The delicate nature of the instrument sensors required that they be protected during the peak entry deceleration and intense entry heating, but exposed to the atmosphere as the probe descent slowed to acceptable levels to allow the instruments to operate properly.

The design of the three Small Probe doors, each of a unique configuration, proved to be extremely challenging. Each had to open in a controlled manner, via an actuation mechanism with adequate torque as the

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probes descended through the thick Venusian atmosphere. If deployment occurred too quickly, the doors would break off and perhaps impact the probe, damaging a window or other external element. If the door were to open too slowly, the resultant torque could possibly fail to overcome the atmospheric forces. Extensive engineering and development finally resulted in doors that passed rigorous qualification testing.

9. GALILEO PROBE INTRODUCTION

Project Galileo began in the mid-1970s, when NASA and the science community were considering the next steps in planetary exploration. Although the Pioneer Venus hardware program had yet to begin, it appeared to be headed toward reality. Scientists naturally turned their sights towards the most readily accessible giant planet, Jupiter. Rather than fly an orbiter vehicle and a separate probe carrier spacecraft, as on Pioneer Venus, the Galileo mission evolved as a single Orbiter spacecraft that also served as the transport vehicle for the single Galileo Probe. Congress approved funding for the Galileo mission in 1977; in September 1978, as the Pioneer Venus spacecraft were heading towards Venus, Hughes was awarded the contract for the Galileo Probe.

A major redesign of the Galileo Probe occurred during the system-level preliminary design review (PDR), presented by Hughes and NASA Ames. JPL management was very concerned that a single Galileo Probe with a single string design, as flown on the Pioneer Venus Large Probe, was susceptible to a single point failure that would greatly limit the probability of a successful mission. As a result of the review, JPL management required that the Galileo Probe be designed for dual string operation so that a single point failure in one string would not severely limit the science data transmitted by the Galileo Probe.

It is interesting to note that the single spacecraft mission design was nearly derailed early in the program when the combined mass growth of the Galileo Probe and Orbiter appeared to be too heavy to allow the combined mission to proceed. NASA was so concerned with the possibility that the Orbiter and Probe missions could not be supported on a single vehicle, that an RFP was issued for a probe carrier vehicle, separate from the Galileo Orbiter. Hughes, along with other bidders, conscientiously developed a carrier design and submitted a proposal. Although Hughes was eventually selected as the winner of the competition, NASA later determined that there was inadequate funding to complete both the Galileo Orbiter and probe carrier/probe missions. The Galileo mission was restructured to accommodate the original plan of the combined Orbiter/Probe vehicle.

The Galileo mission was in jeopardy again when safety considerations, instituted as a result of the 1978 Space Shuttle Challenger disaster, precluded flying the Centaur upper stage. Without the thrust provided by a powerful upper stage, a direct flight to Jupiter was not possible. JPL engineers saved the Galileo mission by utilizing a unique computer program that created the VEEGA or Venus-Earth-Earth Gravity Assist mission. This unique mission plan resulted in a Galileo space shuttle launch on October 18, 1989, that propelled the combined Galileo Orbiter and probe towards Venus. Passing near Venus, the Galileo mission took advantage of the slingshot affect to retarget the spacecraft towards Earth. Passing near the Earth, the Galileo spacecraft was propelled to the asteroid belt. Using on-board propulsion to provide a change of direction delta V, the Galileo Probe again passed close to Earth where another slingshot velocity boost propelled the Galileo spacecraft on its final trajectory to Jupiter. The Galileo Probe was separated from the Orbiter on July 13, 1995 and entered the Jovian atmosphere nearly 150 days later on December 7, 1995.

10. GALILEO PROBE STRUCTURAL DESIGN

The Galileo Probe structural design borrowed heavily from the Pioneer Venus Large and Small Probe designs. Although the Jovian atmosphere is not as dense as the atmosphere on Venus, it nonetheless required a substantial structure to absorb the entry heat. As the Galileo Probe entered the Jovian atmosphere, it would be traveling at 48 km/sec, over four times faster than the Pioneer Venus probes. But since the upper reaches of Jupiter's atmosphere are thinner than the equivalent atmosphere at Venus, the Galileo Probe would sustain a deceleration of 250 g's, somewhat less than the 458 g's experienced by one of the Pioneer Venus Small Probes.

The Galileo Probe major elements are shown in Fig. 7. The deceleration module aeroshell structure was based on the Pioneer Venus design in that it utilized the identical 45° half angle blunt cone design, a carbon phenolic ablative material and structural elements quite similar to those flown on the Pioneer Venus probes. Due to the large number of science instruments and their requirement to sense the atmosphere under various conditions, it was necessary to extract the Galileo Probe descent module, containing the housekeeping and science instruments, from the deceleration module in a manner identical to the Pioneer Venus Large Probe technique. Thus, a mortar fired pilot parachute separated the descent module aft cover, which in turn extracted the main parachute. Unlike the Pioneer Venus Large Probe, which jettisoned its parachute within seventeen minutes of deployment, the Galileo Probe retained its parachute for the entire mission.

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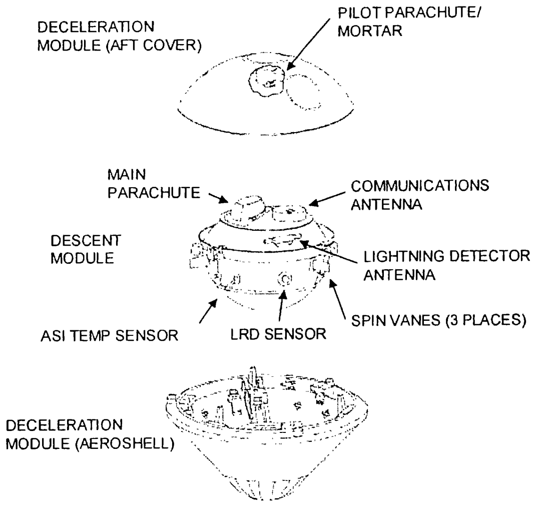

Fig. 7. Galileo Probe Major Elements

The Galileo Probe thermal design differed substantially from that on the Pioneer Venus probes. To begin with, the Galileo Probe deceleration module incorporated radioisotope heater units, or RHUs, to maintain the probe science instruments and subsystems above their temperature limits during transit between Earth and Jupiter and the long 150-day coast period between separation from the Galileo Orbiter and descent into the Jovian atmosphere. Because the Galileo pressure and temperature requirements were far less than those for the Pioneer Venus probes and to minimize the additional weight added by a pressure vessel, a vented probe design was selected. Each individual instrument and probe subsystem unit was sealed to protect their electronics from the Jovian atmospheric gases ingested by the probe. The thermal blanket system, required to maintain the probe electronics at the required operating temperatures during the cold and hot phases of the mission, was held in place by a multipiece, circumferential blanket retainer, in a manner similar to that used on the Pioneer Venus Large and Small Probes. In addition, unit and structural masses served as transient heat sinks throughout the Galileo Probe, as they did on the Pioneer Venus probes. A design summary of the Galileo probe is provided in Table 4.

11. GALILEO PROBE SUBSYSTEM DESCRIPTION

Fig. 8 depicts the Galileo Probe general arrangement. The electrical design differed substantially from the simple design on the Pioneer Venus probes. To begin with, the Galileo Probe utilized a battery technology, still under development at that time. Although $LiSO_2$ is a standard battery that is now commonly flown in entry vehicles, such as the Mars MER Rovers and the Huygens probe, it was relatively new in the 1980s when the Galileo Probe was designed. The Galileo Probe also flew thermal batteries. These power sources provided the high current capacity to the pyrotechnic control unit (PCU) that in turn generated the pulses to fire the pyrotechnic initiators, required to ignite the pilot chute mortar and separate the descent module from the deceleration module.

Table 4. Galileo Probe Design Summary

Total Mass	339 kg
Deceleration Module	213 kg
Descent Module	126 kg
Diameter	
Deceleration Module	126 cm
Pressure Vessel	66 cm
Main Battery	3– 13 cells packs, 22 A-h, $LiSO_2$
Thermal Battery	2– 14 cells packs, 37 V, $Ca/CaCrO_4$
Date Rate	128 bps
Science Accommodation	
Inlets, outlets	5
Windows	4
Deployments	1
Science Instruments	7 total, 30 kg, 26 W
ASI	Atmospheric structures inst.
NEP	Nephelometer
HAD	Helium abundance detector
NFR	Net flux radiometer
NMS	Neutral mass spectrometer
LRD	Lighting and radio emission detector
EPI	Energetic particle instrument

Two separate power-switching units were flown, due to the differing electrical requirements for the science instruments and the probe housekeeping units. The instrument power interface unit, or IPIU, provided prime and redundant power conditioning and overvoltage protection for the powering the science instruments. The subsystem power interface unit (SPIU) was much simpler, since it provided switched, unconditioned power, directly from the battery, to the various probe subsystems, as well as deriving probe current telemetry.

In contrast to the simplified CDU design in the Pioneer Venus Large and Small Probes, the data and command processor (DCP) flown on the Galileo Probe was a highly complex, processor-based system that generated two telemetry strings (A and B) to satisfy the redundancy requirements imposed during the system PDR. The DCP, housed in a single chassis, was effectively two half units, with each independent string powered by its own power supply. Although the A and B strings were identical in their handling of command and telemetry functions for the probe subsystems and science instruments, the B-string functioned only during the entry and descent phases of the mission. The coast timer, which operated between separation from the Galileo Orbiter and probe wake-up prior to entry, was implemented in the A-string only. Fault management for the two strings was implemented in a self-test analyzer, initiated by turn-on of the B string that provided a one-

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time assessment of each string with the capability to disable a faulty string. As in the Pioneer Venus probes data and command subsystem design, the Galileo Probe DCP provided data storage for pre-entry and initial entry data, which was played back during the descent phase of the mission. The DCP generated three telemetry formats, one for use in storing the data accumulated during the entry phase of the mission and the second for use during the descent phase of the mission. A third format, used during testing, provided the capability for accelerated readout of the DCP memory. All three formats generated data at 128 bps.

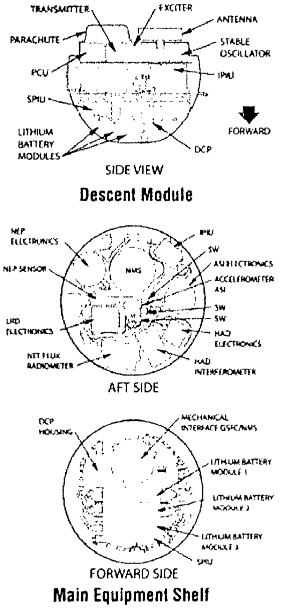

Fig. 8. Galileo Probe General Arrangement

The Galileo Probe telecommunications subsystem also generated dual RF signals, to meet the dual string requirement for the probe. The A-string consisted of a stable oscillator, an exciter and a transmitter. The B-string telecommunications was nearly identical, with a temperature compensated crystal oscillator rather than a stable oscillator as in the A-string. Each provided 24 watts of S-band RF power in oppositely polarized signals, that were combined in a hybrid for transmission to the Orbiter using a single probe antenna.

12. GALILEO PROBE INSTRUMENT ACCOMMODATION

Accommodation of the seven Galileo Probe instruments, listed in Table 4, required a multitude of inlets and windows for atmospheric sensing. These included four inlet ports, one outlet port (for the NMS), four windows and a single deployable arm for the nephelometer. Late in the program, during the final testing of the separation system, interference between a severed descent module umbilical and the NFR field-of-view, was observed. Engineers quickly designed a dual-spring retraction mechanism, as well as reducing the wire gauge size, to ensure no obscuration of the NFR sensor would occur.

13. GALILEO PROBE MISSION DESCRIPTION

The probe mission sequence is summarized in Fig. 9. Science data collection occurred throughout the pre-entry and entry phases of the mission. The ASI and LRD were powered approximately 6 hours before entry, while the remaining instruments began their data collection after extraction of the descent module from the deceleration module while on the main parachute.

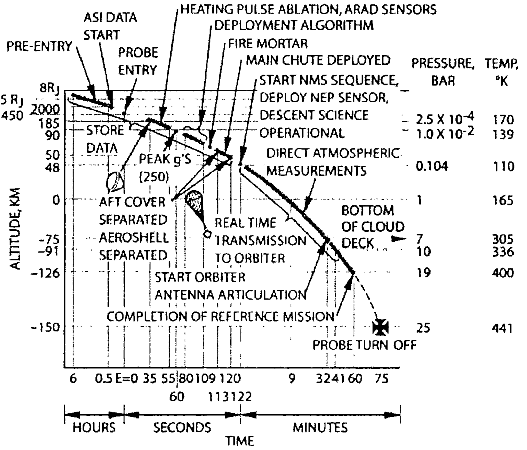

Fig. 9. Galileo Probe Mission Sequence

14. LESSONS LEARNED

There are many lessons to be learned from the experiences of designing, fabricating, testing and delivering five planetary entry probes for the Pioneer Venus and Galileo Probe programs. The first and most obvious point is to tailor the probe mechanical design requirements to the specific mission. The severe Venus environment, as well as the corrosive atmospheric elements, required that the Pioneer Venus probes be sealed pressure vessels. This technique allowed the thermal design to close while providing the probe subsystems and science instruments with relatively benign thermal and chemical environments.

Considerable deceleration resulting from high-speed entry into planetary atmospheres also drives the mechanical configuration. All electronics units must be carefully designed and thoroughly tested in excess of the predicted deceleration to ensure they will survive the probe mission. Other probe elements, especially harnesses, must be thoroughly constrained to prevent failures during planetary entry.

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The thermal design of a planetary entry probe is the second most challenging element. At Venus, the temperature extremes were dramatic, necessitating the use of sophisticated metals, complex thermal blanket designs and intricate mechanical features to absorb the dissipated heat. The thermal design of the Small Probe could not make use of the relatively common nitrogen internal atmosphere technique as on the Large Probe. Xenon, a high-molecular weight gas that greatly limited the heat transfer by convection and conduction, allowed the thermal design to close by maintaining all units within their proper operating temperature. The fact that one of the Small Probes, designed to descend through the Venus atmosphere, but not survive landing nor operate on the surface, continued to transmit after landing for over an hour, is testimony to the robustness of the thermal design and fully justified the intense effort expended in fine-tuning the system design of the Small Probe. The superb thermal designs of the Pioneer Venus probes resulted in all probes performing at or below their thermal predictions.

Design of the support electronics for planetary entry probes must be kept in perspective. Although the state-of-the-art electronics can support sophisticated data processing, with attendant control functions, these advanced techniques may not be warranted for the probe design. The emphasis on electronics sophistication should be in the science instrument design – not in the design of the probe subsystems. The Pioneer Venus probes made use of simple command and data handling (C&DH) processing that supported the scientific objectives of the mission. On the Galileo Probe, a more sophisticated C&DH design was implemented. This increased capability provided more flexibility for the science instruments, but also allowed numerous changes to be made in the sequences throughout the development program. These changes, in turn, required additional test time and thus ended up costing more than a simpler system.

High data rates are not necessarily required on planetary entry probes. Although imaging instruments may generate data that necessitates kilobit/second rates, the Pioneer Venus and Galileo Probes data streams were all well below this level. Again, the C&DH requirements must be tailored to the science instrument data processing rates.

A note on battery technology is also in order. For the Pioneer Venus probes, AgZn secondary batteries were used. This battery design required access to the batteries, through the Multiprobe Bus, while on the launch pad, to ensure that the batteries were fully charged prior to launch. On the Galileo Probe, a $LiSO_2$ primary battery was used. Primary batteries do not require recharge and retain their charge over extremely long periods of time. This was dramatically demonstrated on the long Galileo mission: the Galileo Orbiter with its probe was launched on 18 October 1989, with the probe finally entering the Jovian atmosphere over 6 years later on December 7, 1995. The probe power subsystem operated without problems throughout the probe descent.

Although $LiSO_2$ battery technology was relatively new at the time of Galileo Probe development, it has since become the industry standard for planetary entry probes currently flying on the MER program and the Huygens probe. Since the Galileo Probe first flew $LiSO_2$ battery cells, this battery design has greatly matured, reducing the cost of flying these cells on subsequent missions.

Another lesson concerns testing. Throughout the development programs on the Pioneer Venus and Galileo probes, environmental testing was conducted in conditions as close as possible to the planetary entry requirements. This testing revealed design weaknesses and allowed the structural and thermal designs to be fine-tuned to the actual mission environments. The old adage, "test what you fly and fly what you test" greatly benefited both programs. Relatively obvious design oversights, such as the severed cable interfering with the instrument operation, as mentioned earlier, would not have been found without testing on flight hardware in the flight configuration.

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