ASCI 509 – Graduate Report
History of Planetary Probes: Aerodynamic Designs for Atmospheric Entry
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Abstract

Through this report, the researcher proposes to render a brief history on the evolution of the planetary probes, utilized for scientific research of planetary satellites within our solar system. The outcome should provide the reader with a clear notion of the evolution in design, as to the aerodynamic properties and concepts considered. A brief analysis will also be put forth as to the application of new technology to modern probes to further explore said bodies with applied aerodynamic concepts.

Since the most important unresolved questions regarding Solar System evolution and planet formation can best be addressed by measurements carried out from atmospheric entry probes and/or surface landers, this report will try to answer questions such as: What new design concepts are currently being designed? What new aerodynamic designs will most likely be implemented for future probes to make them even more efficient?

Introduction

The desire for humans to explore and research the skies has been present since the dawn of mankind, where our ancestors constantly glanced at the night skies wondering, what is out there and how everything works. While curiosity has always been present and will always be in our nature, it is only in recent times that mankind has been able to take the next step and be more proactive in satisfying this curiosity, more so with the advent of science and technology.

Aerodynamics, considered as the science that studies the flow of air, came as a derivation of our invention of flight. Years later, it can be argued that the space industry was the next logical step in our technological flight evolution.

In this sense, the space industry has experienced a tremendous growth since the 1950's, and this all derives from the first probe to go into space. Unlike the delayed impact on society of the first flight by the Wright brothers in 1903, the launch and success of the first artificial satellite by the Soviets, Sputnik I, had indeed an immediate positive response worldwide.

In order for the human race to further explore our solar system and distant satellites in years to come, the most efficient and aerodynamically suitable probes will need to be created, each adapted to the specific mission at hand, and inherently adapted to the atmospheric conditions of the object it will encounter.

In this sense, it is the researchers' intentions to provide hereunder a laconic evolution of said probes, what has been done aerodynamically and what is under planning ahead, so that future generations of aerodynamicist and aeronautical engineers can have a clear background on the subject.

First Planetary Probes:

Sputnik 1 was launched by the Soviet Union in 1950. It became the first artificial satellite of Earth.

According to the Jet Propulsion laboratory (1993), the probe had one watt of power, producing a 0.4 second duration signal on the 7 and 15 m bands. Four antenna were deployed at 35 degree angles. Power was provided by three silver-zinc batteries. Thermo-regulation was by a ventilator. The 580 mm sphere had a mass of 83 kg and was made of highly polished Aluminum AMG6T alloy 2 mm thick. It was built without drawings due to the quick time schedule.

Although Sputnik 1 was not the first to experience atmospheric entry to another planet, it did however represent a great leap in thinking, since it was the first manmade artificial satellite. Only twelve years later people had walked on the moon; within another seven years unmanned probes were already present at the surfaces of Venus and Mars (Anderson, 2010).
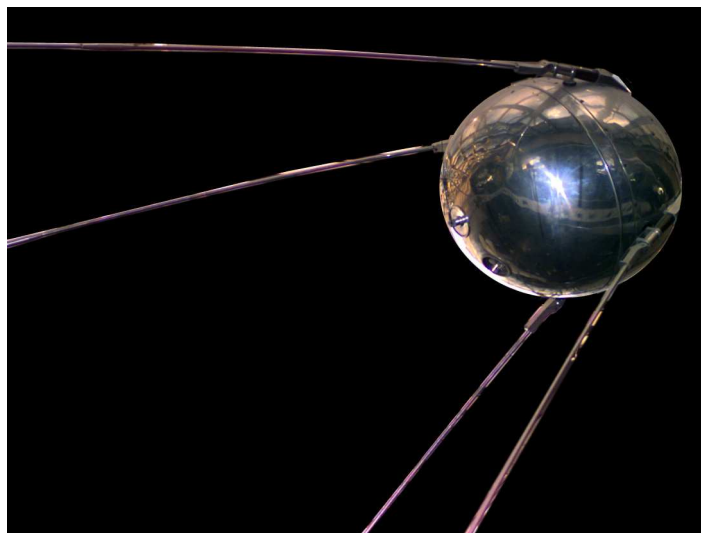

FIGURE 1-1: Sputnik I
Courtesy: NASA (2003).

First Probes to Encounter Atmospheric Entry:

Since the report at hand is focused on the aerodynamic characteristics of planetary probes, the researcher will only limit the writing to those specific probes that first encountered atmospheric resistance during entry, and thus required aerodynamic designed for their successful missions.

- Soviet Probes

Between 1961 and 1984 the Soviet Union launched a series of probes to gather data from Venus. In total ten probes were successfully launched under the name "Venera" probes.

The Venera 7, designed to survive Venus surface conditions, was the first probe landing on another planet and to make a soft landing. Massively overbuilt to ensure survival, it had few experiments on board, and scientific output from the mission was further limited due to an internal switchboard failure which stuck in the "transmit temperature" position. Still, the control scientists succeeded in extrapolating the pressure (90 atm) from the temperature data (465 °C (869 °F), which resulted from the first direct surface measurements. The Doppler measurements of the Venera 4 to 7 probes were the first evidence of the existence of high-speed zonal winds (up to 100 metres per second (330 ft/s) in the Venus atmosphere.

Venera 7's parachute failed shortly before landing, fortunately very close to the surface. It impacted at 17 metres per second (56 ft/s) and toppled over, but survived. Due to the resultant antenna misalignment, the radio signal was very weak, but was detected (with temperature telemetry) for 23 more minutes before its batteries expired. Thus, it became, on 15 December 1970, the first man-made probe to transmit data from the surface of Venus.
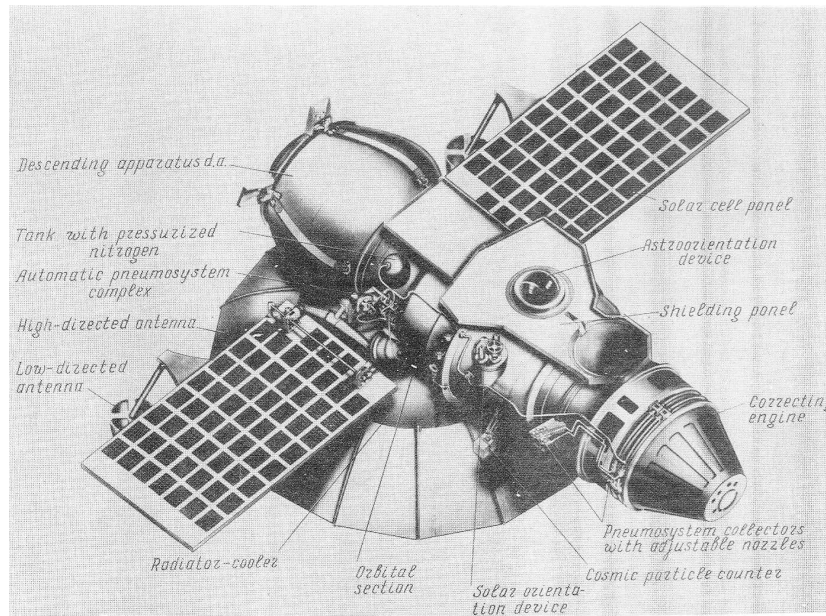
Fig. I. Automatic Interplanetary Space Station   Venera 7

FIGURE 1-2: Venera 7 Probe.
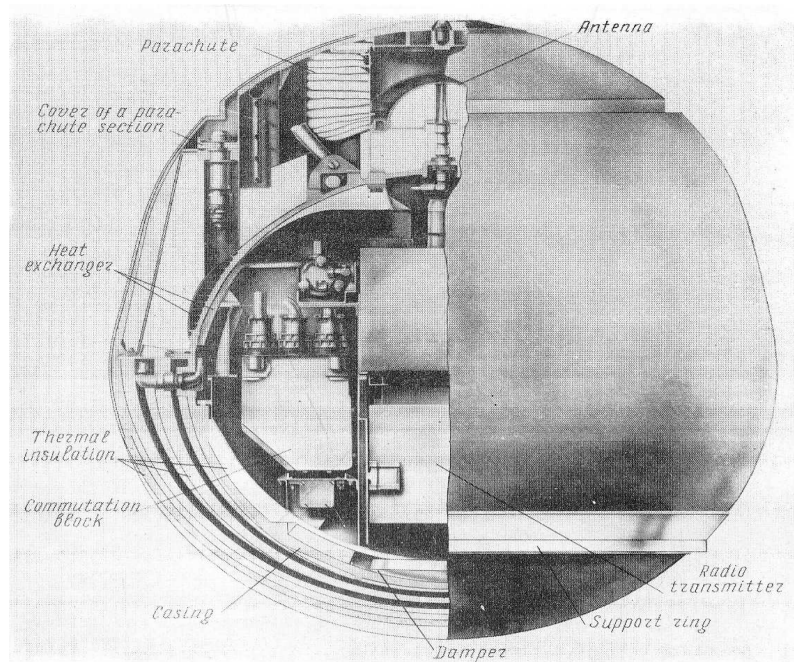Courtesy: Kerzhanovich, Viktor, Jet Propulsion Laboratory (2003).

Fig. 2. The descending probe   Venera 7

FIGURE 1-3: Venera 7 Probe Entry Vehicle.
Courtesy: Kerzhanovich, Viktor, Jet Propulsion Laboratory (2003).

As to the dynamic of descent and reconstruction of trajectory, the following equations were considered:

$$V_D = -c\,\frac{f_D}{f_0} - V_{ir} - \frac{1}{c}\left(\frac{V^2}{2} - V_{ir}^2\right)$$

The above equation measured:

- The component of the vehicle in direction of receiver

- Knowledge of transmitted frequency *fo* ; stability of USO – main error factor.

- *VD* = velocity in atmosphere when orbital motion and propagation effects subtracted = descent velocity + wind drift.

  = Velocity of descent when receiver is near zenith

  = Wind velocity when velocity of descent subtracted

- Vehicle aerodynamics effects

The Venera 9 to 12 probes were of a different design. They weighed approximately five tons and were launched by the powerful Proton booster (Kerzhanovich, 2003). They included a transfer and relay bus that had engines to brake into Venus orbit (Venera 9 and 10, 15 and 16) and to serve as receiver and relay for the entry probe's transmissions. The entry probe was attached to the top of the bus in a spherical heat shield. The probes were optimized for surface operations with an unusual looking design that included a spherical compartment to protect the electronics from atmospheric pressure and heat for as long as possible. Beneath this was a shock absorbing "crush ring" for landing. Above the pressure sphere was a cylindrical antenna structure and a wide dish shaped structure that resembled an antenna but was actually an aerobrake (Kerzhanovich, 2003).

They were designed to operate on the surface for a minimum of 30 minutes. Instruments varied on different missions, but included cameras and atmospheric soil analysis equipment. All four landers had problems with some or all or their camera lens caps not releasing.

Summary:

- Entry Angles 43-65˚
- Mass 400-500 kg
- Egg-Shaped ~ 1 m Diameter
- G-Loads 400-500 g
- Bare-Bone Science Sensors
- Mechanical & Telemetry
- L-Band Direct-to-Earth 1 bit/s
- Venera 4-6 were crashed by Pressure at 25-20 km
- Venera 7 and Venera 8 landed and survived on the surface 23 and 50 min, respectively.

- United States' Probes:

Explorer 1 was the first successful Earth satellite of the United States, launched as part of its participation in the International Geophysical Year. The mission followed the first two Earth satellites the previous year, the Soviet Unions' Sputnik I and II, beginning the Cold War Space Race between the two nations (NASA, 2008).

Explorer 1 was launched on January 31, 1958; and according to NASA (2008), data from the scientific instruments was transmitted to the ground by two antennas. A 60 milliwatt transmitter fed a dipole antenna consisting of two fiberglass slot antennas in the body of the satellite operating on 108.03 MHz, and four flexible whips forming a turnstile antenna were fed by a 10 milliwatt transmitter operating on 108.00 MHz.

Viking 1 was the first United States' satellite designed for atmospheric entry to another planet. It successfully landed on Mars in 1976 and performed its mission, and holds the record for the second longest Mars surface mission of 6 years and 116 days (NASA, 2008).

According to NASA (2008), the lander and its aeroshell separated from the orbiter on July 20. At the time of separation, the lander was orbiting at about 4 km/s. The aeroshell's retrorockets fired to begin the lander deorbit maneuver. After a few hours at about 300 km altitude, the lander was reoriented for atmospheric entry. The aeroshell with its ablative heat shield slowed the craft as it plunged through the atmosphere. During this time, entry science experiments were performed by using a retarding potential analyzer, a mass spectrometer, and pressure, temperature and density sensors.
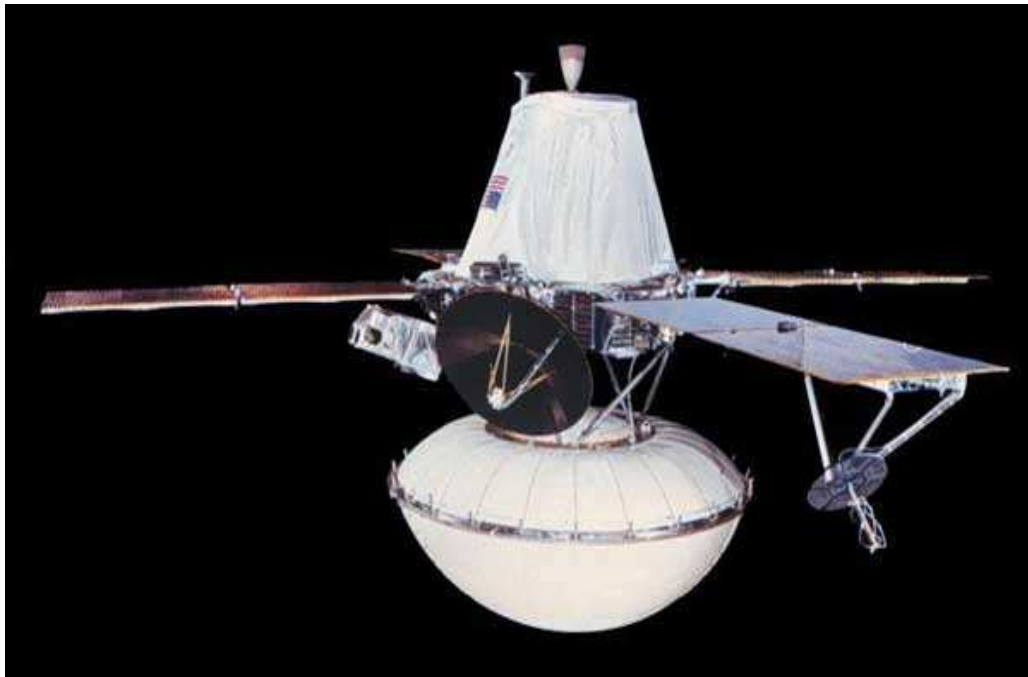

FIGURE 3-1: Viking I
Courtesy: NASA (2008)

The landing rockets used an 18 nozzle design to spread the hydrogen and nitrogen exhaust over a large area. NASA calculated that this approach would mean that the surface would not be heated by more than one degree Celsius, and that it would move no more than 1mm of surface material. Since most of Viking's experiments focused on the surface material a more straightforward design would not have served.

Early Aerodynamics Considerations during High-Speed Entry:

Early NASA missions, such as the manned Gemini and Apollo missions, and the Viking Mars mission, employed new ablative materials for thermal protection systems (TPS) that were tailored for the particular entry environment. After the Mars Viking mission, NASA essentially ceased sponsoring ablative TPS development, and adopted what was basically a "risk adverse" philosophy relative to TPS. In effect, the policy was to use materials that had been used before even if they were not optimal (Young, 2003).

The focus shifted to reusable TPS for the Space Shuttle. Entry probe missions, such as the Pioneer Venus Multiprobe mission and the Galileo Probe mission to Jupiter, employed ablative materials, and used what is termed a fully dense carbon phenolic material that had been developed for ballistic missile applications by the US Air Force. As a consequence of the NASA policy, the ablative TPS community slowly disappeared.

According to Young (2003), the flight missions Stardust and Genesis employed newly developed TPS material. However, the TPS capability developed for either of these missions was very much less than that required for either Venus or outer planet missions in terms of peak heating during entry, or total heat load encountered. Therefore, the TPS technical demands for

Stardust and Genesis were not drivers of technology development as are the TPS technical demands for entry probe/lander missions to Venus or the outer planets.

Modern Atmospheric Entry Probes:

A more recent example of an artificial design for atmospheric entry was the Mars Pathfinder launched on December 4, 1996 by NASA, aboard a Delta II booster. It landed a seven month after it was launched on July 4, 1997 (NASA, 2008).

Mars Pathfinder directly entered the Mars atmosphere in a retrograde direction from a hyperbolic trajectory at 6.1 km/s using an atmospheric entry aeroshell (capsule) that was derived from the original Viking Mars lander design (NASA, 2008).
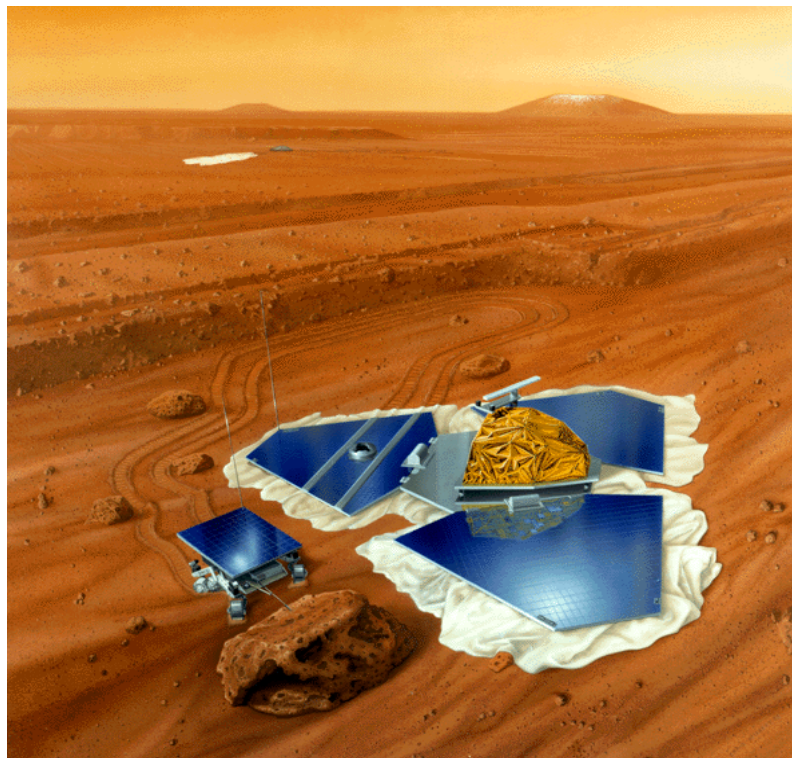

FIGURE 3-2 Mars Pathfinder Rover
Courtesy: NASA (2008)

According to Owen (2003), the aeroshell consisted of a back shell and a specially designed ablative heatshield to slow to 370 m/s (830 MPH) where a supersonic disk-gap-band parachute was inflated to slow its descent through the thin Martian atmosphere to 68 m/s (about 160 MPH).

The lander's on-board computer used redundant on-board accelerometers to determine the timing of the parachute inflation. Twenty seconds later the heatshield was pyrotechnically released. Another twenty seconds later the lander was separated and lowered from the backshell on a 20 m bridle (tether). When the lander reached 1.6 km above the surface, a radar was used by the on-board computer to determine altitude and descent velocity. This information was used by the computer to determine the precise timing of the landing events that followed.

Once the lander was 355 m above the ground, airbags were inflated in less than a second using three catalytically cooled solid rocket motors that served as gas generators. The airbags were made of 4 inter-connected multi-layer vectran bags that surrounded the tetrahedron lander. They were designed and tested to accommodate grazing angle impacts as high as 28 m/s (Owen, 2003).

Hereunder we can appreciate a detailed illustration of the atmospheric entry process the Mars Pathfinder underwent, whereby aerodynamic equations were meticulously studied for its design and consequent entry into mars:
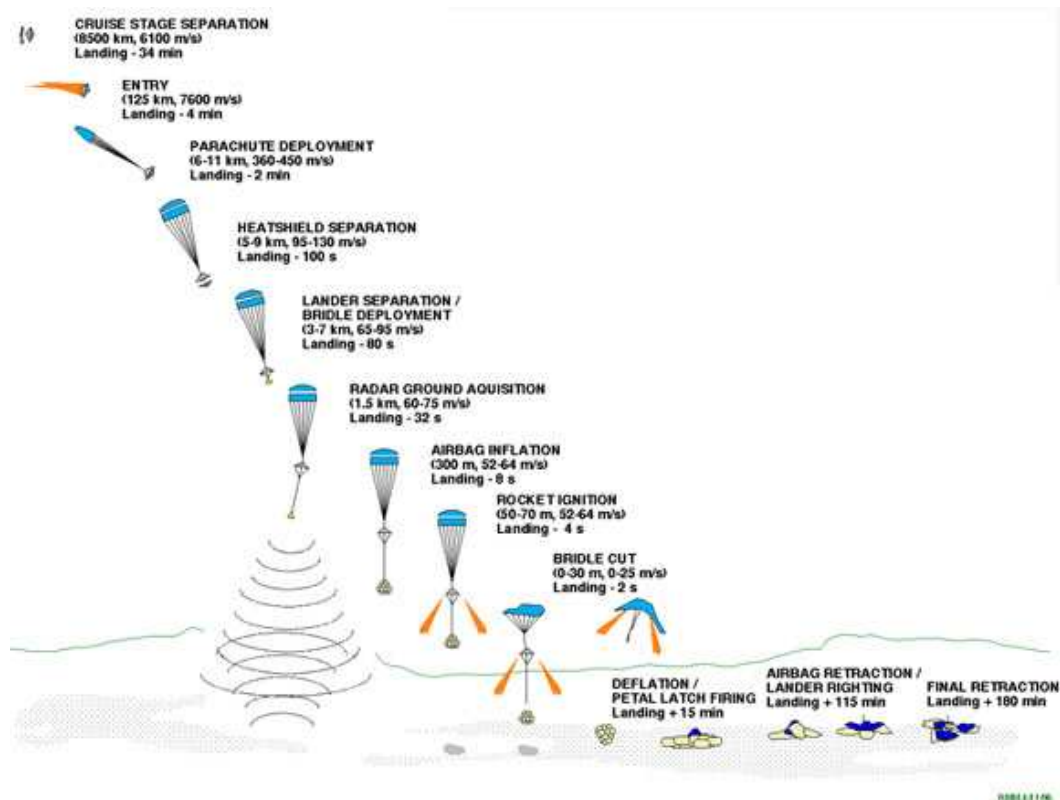
FIGURE 3-3: Mars Pathfinder Atmospheric Entry
Courtesy: NASA (2008)

Aerodynamic Characteristics of Orbit, Trajectory and Entry:

　　　According to Anderson (2010), Earth Satellites launched with enough velocity to go into orbit fall within a required velocity in the order of 26,000 ft/s (7.9 km/s), and these orbits are generally elliptical.

　　　For lunar and interplanetary probes, a launch velocity of 36,000 ft/s (approximately 11 km/s) or larger is required for the probes to overcome the gravitational attraction of the earth and to travel deep into space. Such trajectories are parabolic or hyperbolic. These are first placed in earth orbit, from which it is subsequently boosted by onboard rockets to the desired orbit (Anderson, 2008).

Probes launched from the planets' surface by rocket boosters imply the motion of a vehicle after all stages of the booster have burned out and the probe is smoothly moving through space under the influence of gravitational forces. As follows an important equation considered for such purposes:

Consider a vehicle of mass *m* moving with velocity V in the vicinity of a planet of large mass M. the distance between the centers of the two masses is *r*. Here one of Isaac Newtons' universal gravitation laws can be applied, which states that the gravitational force between two masses varies inversely as the square of the distance between their centers. In particularly, this force is given by:

$$F = \frac{GmM}{r^2}$$

Where G is the universal gravitational constant, $G = 6.67 \times 10^{-11}$ m³ / (kg)(s)².

Also, to consider the potential energy of the small probe's mass *m* in the gravitational field of the large mass *M* at distance *r*, the following equation is considered:

$$\Phi = \frac{-GmM}{r}$$

Where integrating r equals infinity, Φ by definition is is 0, to r = r.

According to Kolesnikov (2003), CFD modeling for atmospheric entry, a catalycity test conditions should be included in the computations of the equilibrium inductively coupled CO2 plasma flow and flow field diameter euromodel and nonequilibrium boundary layer with a finite thickness for 5-species dissociated carbon dioxide mixture or adjusted to the elements of the particular planet.

Numerical analysis of the IPG-4 subsonic carbon dioxide test data within above pressure range should also be considered for the adequate efficiency of the Sibased material increases, if needed.

When the pressure decreases at high surface temperature 1600-1630 K, extrapolation of the ground high-enthalpy test conditions and data of surface catalycity of the planets' entry conditions is to be performed on the basis of the concept of local heat transfer simulation (LHTS).

In order to do that, the results of the characterization of the free stream conditions and CFD modeling of flow field in the plasma torch and around a model must be used. For the three subsonic test conditions at different pressures, the three appropriate sets of the entry parameters (velocity, altitude and nose radius) should also be calculated (Kolesnikov, 2003).

As follows is an illustration of the Galileo Space Probe, whereby we can appreciate a before and after scenario pertaining to the heat shield ablation on atmospheric entry:
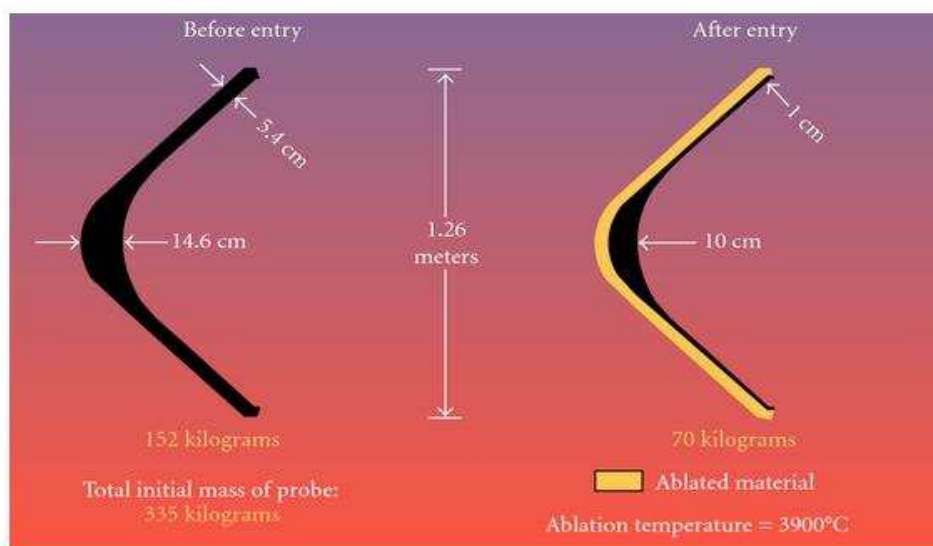
FIGURE 4-1: Galileo probe forward heat shield before and after entry.
Courtesy: NASA (2003)

As oppose to early probes sent out for data collection of our nearby planets, today's' artificial satellites are being designed not only with technologically efficient aerodynamic designs, but they are fitted with multiple data collection tools adapted to their specific mission, such as, but not limited to:

- Solid State Imager (SSI)
- Near-Infrared Mapping Spectrometer (NIMS)
- Ultraviolet Spectrometer / Extreme Ultraviolet Spectrometer (UVS/EUV)
- Photopolarimeter-Radiometer (PPR)
- Dust Detector Subsystem (DDS)
- Energetic Particles Detector (EPD)
- Heavy Ion Counter (HIC)
- Magnetometer (MAG)
- Plasma Subsystem (PLS)
- Plasma Wave Subsystem (PWS)

Future Probe Mission Under Consideration:

Various missions involving entry probes are currently under consideration by both NASA and ESA. To accomplish the kind of progress is desired in the outer solar system. However, there must be a technology development program to ensure that the materials required for heat shields will be available for these probes. Also, further investigation is also required of possible modes for probe delivery, e.g., involving NEP, and methods for deep probe deployment and communication. A combined program of entry probes with varying locations and depths plus pole-to-pole microwave sounding from orbiters or flybys promises the greatest scientific return.

Conclusion

It is clear from that certain high priority science questions concerning evolution of the Solar System and planet formation require the use of atmospheric entry probes/landers. However, as will be described below, if NASA is to have the capability in the next 10-15 years to mount flight missions to Venus or the outer planets that employ entry probes/landers, as recommended by the SSEDS, and as required to fulfill goals and objectives of the Agency's Strategic Plan, NASA must invest in probe/lander technology development. In particular, NASA must immediately invest in thermal protection system development for high-speed atmospheric entry.

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