THERMAL PROTECTION SYSTEM (TPS) EMBEDDED SENSOR TECHNOLOGIES

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ABSTRACT

Planetary probes are used to explore the solar system, search for clues to the origin of life, and study phenomena not observable from Earth. The Thermal Protection System (TPS) protects probes from the harsh atmospheric entry environment. To date, only a few engineering instruments have been embedded into Thermal Protection Systems due to increased complexity and risk concerns. The Galileo probe contained ablation sensors embedded into the TPS. These ablation sensors revealed inconsistencies in the engineering recession models used to predict the Galileo probe's TPS performance. Future entry probe missions, such as those under consideration to Saturn, Venus, and Mars, will benefit from further development of TPS embedded sensors. The goal of this research is to examine the variety of measurements and identify which sensors to embed or place in the proximity of the TPS. These measurements will provide valuable data that will not only help characterize the performance of the Thermal Protection System, but will also contribute to a better understanding of the probe entry environment.

1. THERMAL PROTECTION SYSTEM

The Thermal Protection System (TPS) protects a planetary entry probe from harsh entry environments. New entry probe missions are currently under study by both NASA and the European Space Agency (ESA). These studies are aimed at exploring the planets and moons of the solar system. Entry environment modeling is complex and model verification is necessary to characterize TPS performance. Model verification of the TPS system is difficult because of the extreme conditions and the wide variance of chemical species of the atmosphere during entry. One way to verify the entry models and characterize TPS performance is to measure the TPS entry properties such as recession, temperature, and pressure during a planetary entry.

Sensors have been embedded in Thermal Protection Systems for probe missions in the past, but few probe missions have had a full sensor suite due to concerns for the mission's safety, mass, power budget, and data budget. In 1971, the PAET probe flew a suite of instrumentation into the Earth's Atmosphere "to test the capabilities and to determine the composition of unknown atmospheres during high-speed entry." [13] The success of the PAET probe demonstrated the value of embedded TPS instrumentation for future entry probe missions.

Sensors embedded into the TPS add another level of complexity into the system. The probe's scientific payload is comprised of a suite of instruments with external sensors. The sensors are exposed when the TPS is released from the probe. The probe's payload takes necessary scientific measurements of the planet being explored. The addition of numerous wires for data transmission, power, and communication from TPS embedded sensors adds risk to the heat shield's release sequence. The wires are cut by a pyrotechnic cable cutter before the heat shield falls away. If all the wires are not severed the TPS would not be able to fully clear the craft, resulting in damage to the probe and compromise to the probe's ability to complete its scientific investigation. Additionally, wired TPS sensors add mass, data, and power overhead. Each individual sensor does not contribute a significant amount of the budget, but the addition of multiple sensors and the wiring used to maintain the sensors does come with a potential mass, power, and data penalty.

2. BACKGROUND

2.1. Thermal Protection Systems

The Thermal Protection System (TPS) protects (insulates) a planetary entry probe from the severe heating encountered during hypersonic flight through a planetary atmosphere [1]. The material comes in two primary forms: non-ablative and ablative. Non-ablative tile is a material which soaks up the heat and then re-radiates the heat back to space. Ablative material is material which is burned away during entry [2]. The primary form of TPS for probes the ablative tile which must survive heat fluxes as high as 300 kW/cm^2 [1].

2.2. TPS Materials

Non-ablative TPS is a material where after exposure to the entry environment there are no changes in the mass or properties of the material. Typical, non-ablative TPS applications are limited to relatively mild entry environments (Fig.1) [2]. Non-ablative tiles provide protection to craft such as the Space Shuttle.

Ablative material is burned during entry. During entry, ablative materials undergo three stages: virgin material, pyrolysis, and char (Fig. 2) [2]. The material is considered "virgin" material until it has been affected by heat or radiation as heating increases and pyrolysis begins. During pyrolysis, chemical changes occur and the outer surface of the virgin material is converted into gas and char. The char is a low density solid material which adheres to the remaining material after the pyrolysis phase ends [4].

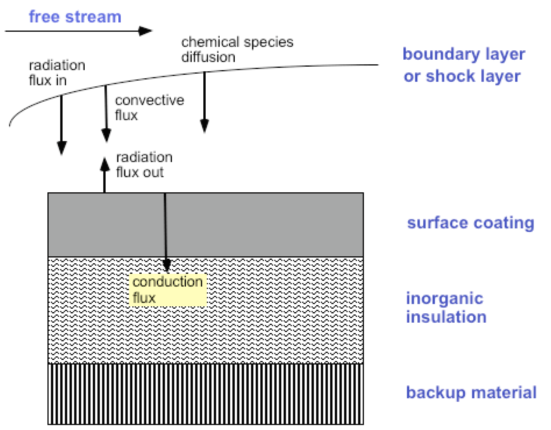

Figure 1. Non-ablative TPS Diagram

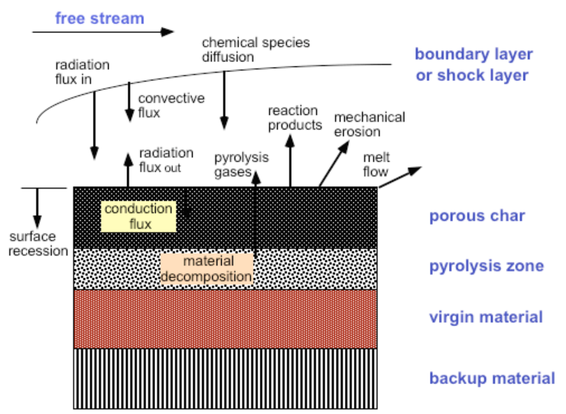

Figure 2. Ablative TPS Diagram

Ablative TPS materials come in many forms such as AQ60, SLA 561 V, and PICA. The AQ60 is a low density (0.28 g/cm^3) ablative material manufactured by European Aeronautic Defense and Space Company (EADS). The material is made from a cork composite of short silica fibers reinforced by a phenolic resin [5]. The adhesive property of the virgin layer allows the char layer to remain on the surface of the tile for a longer period of time. This property is desirable because the char layer provides additional insulation for the probe during entry. The virgin material also provides a strong base to withstand the pressures and loading dynamics of the entry environment. The Huygens probe flew AQ60 successfully to Saturn's moon Titan.

A second type of ablative material is Super Lightweight Ablator 561 V (SLA 561 V); a low-density (0.239 g/cm^3) carbon resin based ablative material manufactured by Lockheed Martin. It has a similar composite composition to AQ60, and has been used on numerous missions including Mars Polar Lander and the Mars Exploration Rovers [6].

Phenolic Impregnated Carbon Ablator (PICA) is a low-density (0.257 g/cm^3) composite ablative tile developed by NASA Ames and was used on the Stardust Earth-return mission [2]. The material comprises carbon fibers impregnated with phenolic resin [7]. The material is the primary material of interest for the Orion Crew Exploration Vehicle which will replace the Space Shuttle in 2011 - 2014.

2.3. TPS Plugs

The Thermal Protection System plug is a small amount of material which is machined to shape to be embedded into the heat shield. The method of embedding TPS sensors is to drill multiple holes into the heat shield and embed a TPS plug into each drilled hole. Each plug can contain up to four thermocouples and one recession sensor machined into TPS material. The plug is then inserted into the drilled region and glued into place with high temperature silica glue called RTV.

2.4 Measurements

The Galileo probe had numerous embedded TPS sensors to measure temperature and recession of the probe heat shield. Temperature was measured by a Nickel-based resistance thermometer bonded to the backside of the front shield. Recession for this flight was measured by the Analog Resistance Ablator Detector (ARAD). The recession models of the Galileo entry predicted the nose of the shield would ablate considerably more than the shoulder region. The data from the ablation sensors revealed this was not the case. The TPS on Galileo recessed 4.4 cm (Fig. 3) [1] in the shoulder region, compared to the estimated ablation value of 3.27 cm [9], leaving a margin of only 1.0 cm. The stagnation point recession model predicted the nose would recede 8.75 cm, but the actual recession value was measured to be 4.13 cm. The recession modeling was overestimated with a safety factor of two, but the recession in the shoulder region could have been compromised if the probe had a steeper entry angle, and the nose showed a considerable margin which is just as problematic because of the unnecessarily large TPS mass fraction. The Galileo TPS investigation serves as an instructive example of why instrumentation should be flown in the future.

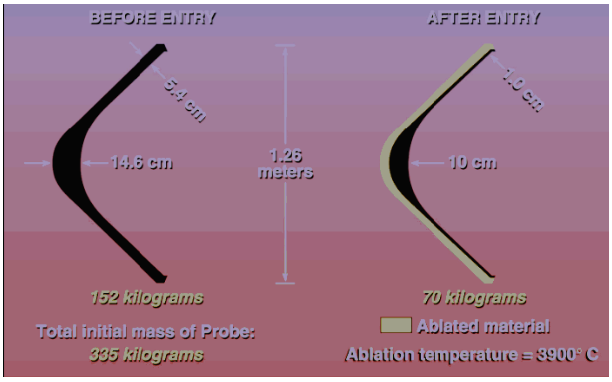

Figure 3. Galileo TPS Ablation Diagram

3. RESEARCH METHODS

The goal of this investigation was to better understand the potential for, the benefits from, and the complexities associated with the implementation of embedded sensor measurement devices. This study examines and evaluates the different measurements and types of sensors embedded within or placed in proximity to the TPS, and explores the contributions of TPS sensors to the entry and descent trajectory analysis, entry science, TPS characterization, and overall mission science. Sensor size, mass, and power requirements are categorized as well as a list of the strengths and weakness inherent to each device.

4. METHODS

Each measurement below is listed in approximate order of importance to aerothermal analysis and potential for overall contribution to mission science and engineering. There are more measurements of interest for future work but this study is limited the list below. Individual measurements are listed with sensor types, mass, power, data rate, and flight heritage.

Measurements of interest include:

1) Recession
2) Temperature
3) Pressure
4) Micro Meteor Orbiting Debris
5) Plasma Electromagnetic Noise

5. RESULTS

5.1. Recession

Recession is the amount of TPS material which is ablated during entry. The recession measurement shows how the TPS shield mass and shape changes during the entry. The amount of material which remains after the entry is also of interest to help optimize TPS sizing.

Recession is currently measured on probes by one of two sensor types. The Analog Resistance Ablation Detector (ARAD) or the Hollow aErothermal Ablation Temperature detector (HEAT) are the two most common types of sensors used to measure recession. Both sensors use two coils of resistance wire wound around a plug of ablative material. A hole is drilled into the TPS plug and the ARAD/HEAT sensor is glued into place with the RTV bonding agent. When the plug starts the ablation process a char layer is formed. The char layer is electrically conductive and completes the electrical circuit between the two coils of wound wire. The wire is provided with a constant current and the voltage is measured and provides an indication of the thickness of the TPS. The HEAT sensor was designed to have a higher signal to noise ratio to help alleviate the problems associated with the ARAD measurements on Galileo.

The Galileo probe flew the ARAD sensor package. These sensors had multiple failures on the Galileo mission for unknown reasons [1], but it is suspected there was a high level of noise to signal which contributed to the failures. One possible reason for the failures is the electrostatic discharge interfering with the resistance values. The HEAT sensor was developed to overcome the shortcomings of the ARAD sensor package, and is expected to fly on the Mars Science Laboratory (MSL). The project is called the MSL Entry, Descent, and Landing Instrumentation or MEDLI.

Recession might also be measured by ultrasonic transducers and receivers [12]. This method of recession measurement has not been used in a planetary probe environment. The ultrasonic transducer produces an ultrasonic compression wave through the TPS material. A part of the compression wave is reflected back toward the receiver when it reaches the end of the material. The time of flight of the compression wave is measured and correlated with the TPS thickness. For example, a person throws a rock into a pond, and the ripples radiate out from the point of impact. The time for the ripples to reach shore and return is measured. The time measurement can then be used to calculate how far the shore is from the where the rock stuck the water. The same is true for a compression wave through a solid material.

Further investigation should be pursued into this method of recession measurement. One benefit is the non-destructive nature of an ultrasonic transducer. The sensor can be mounted on the backside of the TPS by a bracket or bonding agent. Data rates, mass, error, and mounting ramifications are not yet known [12].

5.2. Temperature

Temperature is a measurement of the heat through the TPS material. This measurement gives the TPS engineers information on how the TPS material is responding in the entry environment. Multiple measurements at different depths in the same location will define how heat is conducted through the TPS material.

The primary method of measuring temperature is with the thermocouple. Thermocouple sensors work by measuring the voltage between two dissimilar metals at a specific temperature. The voltage output of a thermocouple changes as a function of temperature, an effect known as the Seebeck Effect. The temperature can only be taken if the temperature of one of the metals is known. The measured voltage is then transformed to a digital signal by a specialized analog to digital converter called a Cold Junction Correction Analog to Digital Converter.

The heat shield material is a good insulator, but generally a poor thermal conductor. The TPS material therefore responds slowly to temperature changes, and is sampled only once every second. A typical thermocouple accuracy is 3% at 1000 degrees Celsius [11] and it has a mass of 5 - 10 grams. The temperature range for a type K thermocouple is -200 degrees Celsius to 1,200 degrees Celsius.

One disadvantage to thermocouples is susceptibility to electromagnetic noise. Noise reduction can be made by converting the analog signal to a digital signal as soon as possible in the circuit. Thermocouples have been flown on numerous missions such a Pioneer and Pathfinder [13].

5.3. Pressure

Pressure measurements are used to calculate the angle of attack. Shear pressures can also be calculated during entry from the pressure measurements. The total pressure is measured by small inlet and connecting tubes in the TPS material. The main sensor used for the entry pressure measurement is the pressure transducer. Pressure transducers utilize an elastic diaphragm and strain gages to measure pressure by means of an air intake which is drilled through the TPS material. Air flow produces pressure on the diaphragm. The deformation of the diaphragm is measured by the strain gages. The strain gages then create a resistance which is then correlated with pressure.

The pressure transducer itself is mounted to the carrier structure behind the TPS. Each transducer has a response rate of 20 ms which correlates to 50 readings per second with an error of 0.01 %. The mass of each transducer is 300 grams and has a current draw of 45 mA [10]. The pressure transducer has been used on numerous missions such as Apollo and Viking [13].

5.4. Micro Meteor Orbiting Debris

The Micro Meteor Orbiting Debris (MMOD) measurement is used for detecting damage inflicted on the TPS from launch or space debris. Measurement are made by accelerometers and piezoelectric materials placed in various areas. If the accelerometer or the piezoelectric material experiences an impact then it locates the location of the impact. To better protect the crew on board, sensors for MMOD impact are used on manned space missions such as the Space Shuttle or the International Space Station [16]. Impact detection for probe missions is of interest to characterize the performance of the TPS during long flights, but these measurements are secondary to recession, temperature, and pressure.

5.5. Plasma Electromagnetic Noise

The hot plasma sheath that forms around a probe during atmospheric entry generates electromagnetic radiation. The electromagnetic noise generated by the plasma sheath has not been studied or characterized in detail. A broadband antenna placed behind the front shield of the TPS would allow a closer characterization of the entry environment. One constraint for this measurement is the TPS has to be RF transparent. A typical broadband antenna mass may be on the order of 100 g - 500 g. The data rate is 50 - 60 samples per second for the supporting hardware with a current draw of 300 mA [15]. There is no flight heritage concerning for this sensor, but the PAET probe flew a radiometer to measure the electromagnetic noise to better characterize RF transmission though the plasma entry environment [13].

5.6. Sensor Placement

Multiple measurement locations are needed to verify the aerothermal dynamic models. The placement of the sensors is dependant on the planned entry geometry. There are two entry configurations: 1) Ballistic entry in which the angle of attack is zero, and 2) lifting entry in which the angle of attack is nonzero this creates lift on the probe like a wing.

In a ballistic entry the probe is spun up prior to release to provide stabilization of the probe and to provide uniform ablation of the TPS. Due to the symmetry of the probe spinning at a zero angle of attack, sensors can be placed symmetrically at different distances from the nose (stagnation point) of the probe. Two sensors are placed at each point for redundancy. The Ballistic Entry is used for most planetary probe missions.

The other entry configuration is called a lifting entry. The angle of attack is not zero, and the craft is not spun like the ballistic entry. Instead the controlled decent uses three axis steering controlled by thrusters to maintain a specified entry attitude called trim. The sensors are placed in a "plus" type configuration. Two pressure sensors and TPS plugs are placed at the stagnation point to measure the angle of attack and measure the thermal performance of the material. Additional sensors are placed in areas of interest to maximize the engineering data (Fig.4 [14]).

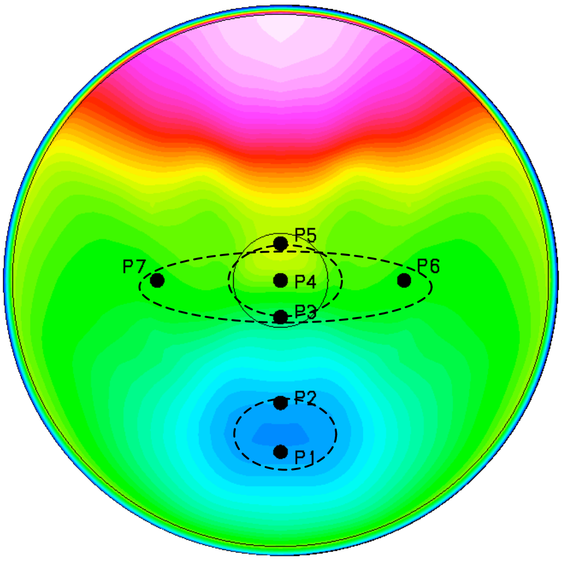

Figure 4. Pressure Transducer Location for MEDLI

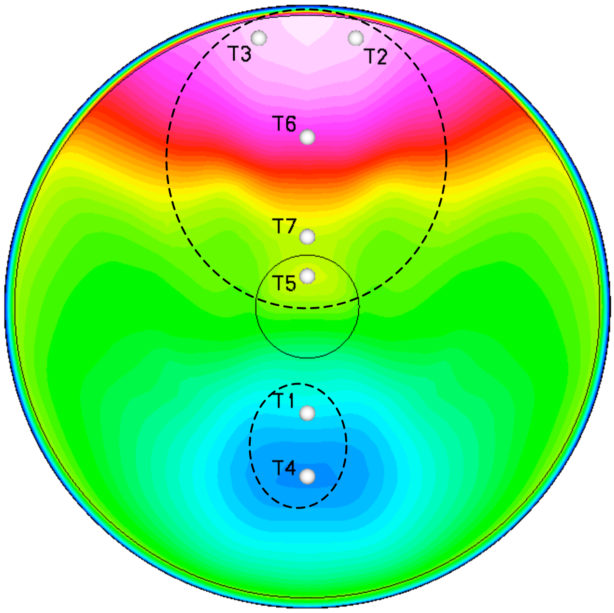

Figure 5. TPS Plug location for MEDLI

6. DISCUSSION

For lander missions such as those to Mars, Venus, and Titan data can be stored and transmitted at a predetermined time once on the craft reaches the surface. Gas planets do not have a surface to land on which makes this mode of operation impossible. The craft vaporizes an hour or two after the mission is finished due to intense heat and pressures of the atmosphere. This limits the amount of data which can be sent during the flight. The hypersonic entry creates a Radio Frequency (RF) opaque plasma sheath which interferes with communication to Earth or a fly by carrier. The data is stored on the probe for this reason, and then it is telemetered back to the carrier or Earth once probe is descending under parachute.

6.1. Saturnian Probe

One probe mission of current interest is to Saturn. Like most planetary probes the Saturnian entry will be extreme like most planetary probes, but will afford the opportunity to test and verify the aerothermal modeling for a Gas Giants entry. The Saturnian entry will be a ballistic entry, and sensor placement will therefore be symmetric around the probe's axis of symmetry. TPS size and geometry will be borrowed from the Galileo probe with a front shield diameter of 1.26 meters with a 45 degree angle [13].

The probe's TPS will be outfitted with an array of sensors which will include instrumented plugs and pressure transducers. All instrumented TPS plugs will contain four thermocouples and one HEAT recession sensor. Each sensor will be placed at a specified distance from the center of the center of the shield (Fig. 6) (Tab. 3), and will have two sensors in specified locations for redundancy purposes. There will be ten TPS plugs of which there will be four redundant plugs. Four pressure transducers will be placed on the backside of the aeroshell two around the nose of the probe and two towards the shoulder.

The TPS will be used for approximately five minutes until the probe reaches its terminal velocity and then the aeroshell is released and the parachute is deployed. The sensor suite will be turned on five minutes before the entry for the baseline readings. Sensor readings will proceed for a total of ten minutes. Data will be telemetered to the flyby carrier once under the parachute. Each thermocouple will be sampled once every two seconds and the data will be stored as an 8-bit number. The pressure transducer will sampled at two times per second. The recession sensor (HEAT) will sample the recession twice per second and the signal will be converted into an 8-bit number. The pressure measurement will also be converted into an 8-bit number. Data volume can not exceed 240,000 bits (Tab. 1). If the data transmit rate is 512 bits per seconds (bps) the transmit time will be eight minutes. The mass for the sensor package is 3,200 grams (Tab. 2) which includes a data acquisition module which has an estimated mass of 1,000 grams. The voltage will be supplied from the probe's 28 Volt power supply, and all power and data lines will go though a single point and be severed by a small explosive device before the TPS is released after the probe has reached its terminal velocity.

The technology is in place for easy integration of the basic measurements of recession, temperature, and pressure. Temperature and pressure sensors have had extensive flight heritage. The recession sensor (HEAT) is still under development, but its development came from the Galileo ablation experiment and is expected to have flight heritage on MSL. The addition of these TPS embedded sensors for the Saturnian entry probe does not contribute a significant amount of data or mass overhead.

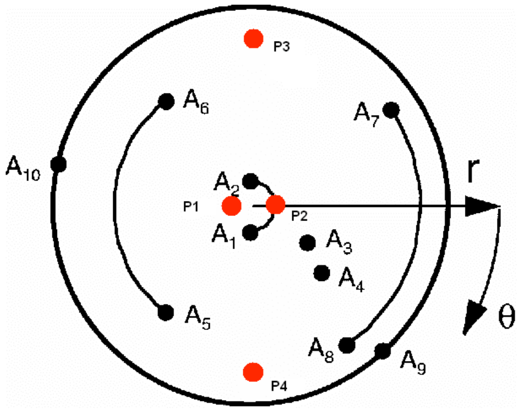

Figure 6. TPS Plug and Pressure Transducer Placement

Instrument Type	Number of Sensors	Sample Rate	Total Samples	Total Data (bits)
Thermocouple	40	0.5	12,000	96,000
HEAT	10	2	12,000	96,000
Pressure Transducer	4	2	4,800	38,400
Totals				230,400

Table 1. Instrumented TPS Data Budget

Instrument Type	Number of Sensors	Mass (g)	Total Mass (g)
Thermocouple	40	20	800
HEAT	10	20	200
Pressure Transducer	4	300	1200
Data Acquisition		1000	1000
Totals			3200

Table 2. Instrumented TPS Mass Budget

TPS Plugs	Location	Pressure Transducer	Location
A1, A2	0.05 m	P1	0.05 m
A3	0.12 m	P2	0.05 m
A4	0.24 m	P3	0.48 m
A5, A6	0.36 m	P4	0.48 m
A7, A8	0.48 m		
A9, A10	0.60 m		

Table 3. Sensor Placement Distances

6.2. Future Work

Future consideration should be given to exploring ultrasonic transducer for recession, MMOD, and TPS performance. Ultrasonic technologies are use in a myriad of nondestructive testing applications for materials. Ultrasonic transducers offer a three dimensional view of TPS recession, and offer's a unique look at the overall status of the TPS. The technology will provide a clear picture of the actual state and therefore should be added to the sensor suite. Entry plasma noise is of interest and should also be considered in order to better understand the plasma entry environment. Upper atmospheric reconstruction may be possible with further examination of the RF noise from the plasma wake. The addition of these two sensors will add value and insight into the entry environment and the TPS performance. These sensors will complement the current set of measurements and should be added if further investigation proves beneficial.

7. CONCLUSION

TPS instrumentation should be placed on every craft going into an atmosphere even if there are limiting circumstances. Recession, temperature, and pressure have had extensive flight heritage and should be continued to be flown on all future missions because of the constraints of current aerothermal testing facilities. Mass, data, and power budgets are of concern, but the information the measurements provide is invaluable in the understanding of the TPS performance and the entry environment. The Galileo probe showed temperature and recession measurements contributed to a better understanding of the Jupiter entry environment and will lead to better performance models for the future missions to Jupiter and the other giant planets [8]. These measurements will provide a not only valuable data set to the engineering and science communities, but will ultimately lead to better TPS performance and mass savings for future missions.

REFERENCES

[1.] B. Laub, E. Venkatapathy, "Thermal Protection System and Facility Needs for Demanding Future Planetary Missions", *Proceedings of the International Workshop on Planetary Entry and Descent Trajectory Reconstruction and Science* given in Lisbon, Portugal, October 2003.

[2.] E. Martinez, E. Venkatapathy, T. Oishi, "Current Developments in Future Planetary Probe Sensors for TPS", *Proceedings of the International Workshop on Planetary Entry and Descent Trajectory Reconstruction and Science* given in Lisbon, Portugal, October 2003.

[3.] C. D. Scott, "Effects of Nonequilibrium and Wall Catalysis on Shuttle Heat Transfer", *Journal of Spacecraft and Rockets*, Vol. 22, No. 5, pp. 489-499, September-October 1985

[4.] R. M. Wakefield, J. H. Lundell, R. R. Dickey, "Effects of Pyrolysis-Gas Chemical Reactions on Surface Recession of Charring Ablators", *Journal of Spacecraft and Rockets*, Vol. 6, No. 2., pp. 122-128, February 1969.

[5.] J. M. Bouilly, "Thermal Protection System of the HUYGENS probe for Titan entry: Qualification, Flight Preparation, and Lessons Learnt", *Proceedings form International Planetary Probe Workshop* given in Attiki, Greece, July 2005.

[6.] E. L. Strauss, "Superlight Ablative Systems for Mars Lander Thermal Protection", *Journal of Spacecraft and Rockets*, Vol. 4, No. 10, pp. 1304-1309, October 1967

[7.] K. E. Parmenter, K. Shuman, F. Milstein, C. E. Szalai, H. K. Tran, D. J. Raskey, "Compressive Response of Lightweight Ceramic Ablators: Phenolic Impregnated Carbon Ablator", *Journal of Spacecraft and Rockets*, Vol. 38, No. 2, pp. 231-236, March-April 2001

[8.] F. S. Milos, Y. K. Chen, T. H. Squire, "Analysis of Galileo Probe Heatshield Ablation and Temperature Data", *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, pp. 298-306, May-June 1999

[9.] F. S. Milos, "Galileo Probe Heat Shield Ablation Experiment", *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, pp. 705-713, November-December 1997

[10.] Mensor Corporation, 6100 Pressure Transducer Data Sheet [Online], Available http://www.mensor.com/pdf/cds6000f.pdf

[11.] Omega Corporation, Thermocouple Resource Page [Online], http://www.omega.com/prodinfo/thermocouples.html

[12.] D.E. Bray, R.K. Stanley, Nondestructive Evaluation: A Tool in Design, Manufacturing, and Service, Boca Raton: CRC Press, 1997

[13.] C. Davies, M. Arcadi, Planetary Mission Entry Vehicles Quick Reference Guide, Version 3, Hanover MD: NASA Center for Aerospace Information, 2003

[14.] N. Cheatwood, et al, "MSL Entry, Descent, and Landing Instrumentation Program Review", NASA Ames, March 2007

[15.] Aaronia AG Corporation, 38080 Log Periodic Data Sheet [Online], http://www.elektrosmog.de/Gutachten/HyperLOG3000-E.pdf

[16.] M. Walcer, "Proposal: Distributed Impact Detection System" [Online], 04-II X4.03-8276, October 2005 http://sbir.gsfc.nasa.gov/SBIR/abstracts/04/sbir/phase2/SBIR-04-2-X4.03-8276.html