WHITE PAPER TO THE NRC DECADAL SURVEY MARS SUBPANEL AND OUTER PLANETS SUB-PANEL

THERMAL PROTECTION SYSTEM SENSORS

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OBJECTIVES AND SIGNIFICANCE

Sensors capable of simultaneous measurement of temperature and heat flux would enable validation and verification (V&V) of ground-based Thermal Protection System (TPS) sizing tools that integrate state-of-the-art computational fluid dynamics (CFD), material response modeling, and ground testing. Currently, TPS sizing V&V is incomplete because ground testing cannot simultaneously match critical aerothermodynamic parameters with flight conditions. Thus, modeling must close the gap between ground and flight conditions, but large uncertainties among the strongly coupled fluid dynamics, gas phase chemistry, and solid state physics models used for simulation propagate directly to uncertainties in heat shield performance requirements, i.e., mass. As a result, very conservative TPS mass margins, 30% - 50%, are required to assure reliable heat shield performance.

New sensor technology will allow lighter embedded TPS sensors. We recommend that NASA support the effort to develop an aeroshell flowfield and heatshield response instrumentation *system* using a mix of existing and new technology that will result in improved performance and reduced mass.

INTRODUCTION AND BACKGROUND

Thermal Protection Systems (TPS) are a single point of failure in any reentry system, and represent an ideal opportunity for feed-forward risk reduction. Mission flights are extremely valuable opportunities to gather data to provide a metric of TPS systems design compliance from requirements through execution. *Traceability is the mechanism by which system compliance of design versus actual risk and performance is demonstrated and measured.* Traceability is accomplished with an unbroken chain of comparisons from ground to flight. The tool to provide design-through-flight traceability for TPS is an *in situ* sensor system.

In contrast to the scientific instruments included in a mission payload, the *engineering* instrumentation system for TPS is primarily of benefit to missions beyond the mission that actually carries the sensors. Historically, a project/mission office has been inclined to view incorporation of TPS engineering instrumentation in their mission as a low priority. From a long-term program perspective, however, the knowledge returned from these instruments represents the engineering legacy of the flight project. TPS flight instruments reduce the risk that future projects will: 1) deliver an inadequate science payload to the target, and 2) suffer vehicle loss through inadequate aeroshell design [1]. Because aeroshell mass trades directly for payload mass, it is of prime importance to employ aeroshell mass with maximum efficiency.

Current state-of-the-art aerothermal design tools incorporate physical models, of varying degrees of sophistication, for the various fluid dynamic and thermochemical relaxation phenomena occurring in the hypersonic shock layers around typical planetary entry probes. These tools also include models for gas-surface interaction. While some of these models are calibrated through experiments in ground-based facilities, they have not been validated against flight measurements because of a paucity of such data. This lack of validation of the physical models is a cost to missions because it leads to incorporation of large design safety margins (increased TPS mass) at the expense of the payload [2].

The key quantities in the design of the TPS are the surface heat flux (convective, catalytic, and radiative), integrated heat load, stress (both pressure and shear), and material response (including ablation rates and/or surface recession). *The fidelity of the physical models would be vastly improved through validation with accurate measurements of these quantities throughout a flight trajectory* and, consequently, the uncertainties/margins in the TPS design would be reduced. The key requirements for sensor development are that the sensors be lightweight and robust (able to withstand the launch and flight conditions and the elevated temperatures during measurement) and that they be equally applicable in both ground-based facilities and in flight (for calibration purposes).

Table 1 demonstrates the NASA heritage of TPS instrumentation, the resulting data, and the benefits to the design of subsequent missions. The utility of flight data cannot be overstated, nor can the limits imposed by its relative paucity. Forty year-old data continues to provide the impetus for and validation of improvements to design tools and methodologies [2]. The lack of TPS instrumentation and flight data from missions-in-progress (MER, Stardust, Genesis, and MSL) represents lost opportunities to improve the design of future Mars and Earth entry vehicles. In order to reduce TPS margins for future missions, *NASA should consider every pass through the atmosphere of a planet as a highly valuable experiment*, expanding the available flight aerothermal database in the aerocapture regime.

Flight data have been of great value in improving our understanding of aerothermal phenomena and the response of the TPS material to such environments. For instance, the observed lack of recession in the heat shields of Apollos 1-6 led to an understanding of the phenomenon of “coking” in the dense TPS material and the consequent lack of recession. The Analog Resistance Ablation Detector (ARAD) sensor successfully flown aboard the Galileo spacecraft provided reliable and important recession data because the flight sensor showed that the recession in the stagnation region was lower than the pre-flight predictions, but that the recession in the shoulder region was much higher than the pre-flight predictions. However, the TPS mass margin in the conservative design was sufficient to ensure a successful flight, though in actuality there was very little margin. The only functioning thermocouple in the aft heat shield of the Mars Pathfinder vehicle demonstrated that TPS mass margins were overly conservative because of an invalid assumption on turbulent afterbody flow. This knowledge led to a decrease in the required TPS margin for the MER vehicle.

Mission	Instrumentation	TPS Mass Fraction	Observations/Resulting Data	Benefits
Apollo 1-3	• 36 pressure sensors • 35 calorimeters	**13.70%**	• Reliable data (early in the trajectory) at orbital entry velocities	• Provided data to improve reliability of entry capsule
Apollo 4&6	• 17 pressure sensors • 23 calorimeters • Stagnation and offset radiometers • Heat shield recovered and sectioned		• Reliable data (early in the trajectory) at super-orbital (Trans-Lunar) entry velocities • Reliable radiation data • In-depth characterization of ablating TPS material – lack of recession due to "coking"	• Flight data available basis for quantifying uncertainty in afterbody heating predictions for a lifting entry with an ablating heat shield • Allowed for optimizing heat shield mass and performance
Galileo	• Forebody recession gages • Afterbody thermocouples	**45.4% (FB) 5% (AB)**	• Largest heat flux and heat load of all planetary missions • Successful demonstration of the ARAD sensor – recession data • Lower than expected recession in the stagnation region • Larger than expected shoulder recession	• Provides the basis for design of the heat shield for Gas Giant entries
Pioneer Venus (4 probes)	• 2 thermocouples in each heat shield	**12.90%**	• Massive ablation in the shoulder region (as in the case of Galileo)	• Provides data for design of TPS in the shoulder region
Viking-I&II	• Backshell thermocouples • Afterbody pressure sensors – limited data	**N/A**		• Provided the basis for Mars Pathfinder TPS design • Provided confirmatory data for CFD – afterbody pressure
Mars Path-finder	• 9 in-depth thermocouples in TPS • 3 resistance thermometers	**6.2% (FB) 2% (AB)**	• 6 functional, including only one on afterbody • 2 functional	• Provided a rationale for MER afterbody heat shield optimization
Fire II Flight for Apollo	• 3 forebody calorimeters • Stagnation and offset radiometers • 12 afterbody thermocouples • 1 afterbody pressure sensor • Rear-facing radiometer	**Flight Experiment Heat shield ejection**	• Surface total heating during portion of entry • Total and spectrally resolved incident radiation to surface • Afterbody heating for entire entry • Confirmed lack of neck radiation at superorbital velocities in air	• Provides validation data for aerothermal/air radiation models • Helps quantify uncertainty in afterbody heating predictions
PAET	• Forebody pressure and heat transfer • Thermocouple in TPS near shoulder • Narrow-band radiometers	**13.7% (FB) 3.5% (AB)**	Spectrally-resolved radiation over several discrete regions	• Validation data for radiation band models • Data for improvement of heating predictions
RAM-C (1-3)	• Microwave receiver/transmitter • Langmuir probes	**Flight Experiment**	• Electron number density and temperature in flight • Quantification of radio blackout – cause and effect	• Validation of CFD models
Space Shuttle STS (1-4)	• Pressure and heat transfer sensors (wind and leeside) • Accelerometers and gyroscopes	**~16%**	• Global and control surface aerodynamics • Demonstration of real-gas effects on vehicle aerodynamics	• Provides data for validation of CFD analysis tools

Table 1 NASA TPS Instrumentation Heritage (FB= forebody; AB= afterbody)

RELEVANCE TO AEROCAPTURE MISSIONS

Aerocapture is becoming an increasingly attractive technology for achieving orbital capture for Mars and Outer Planet orbital missions. "Aerocapture requires extended hypervelocity sustained flight through the atmosphere, placing new demands on the performance of the thermal protection system and requiring other new technologies as well, in connection with guidance, navigation and control, and thermal management." [3] Despite over 40 years of flight experience with reentry systems, significant uncertainties in critical aspects of the aerothermal heating and TPS environment still exist.

The value of instrumentation to measure the aerothermal environment and/or TPS material response during entry and especially aerocapture flight trajectories cannot be overemphasized. The sources of the aggregate TPS margin are uncertainties in fluid dynamics modeling, gas phase chemistry modeling, gas-surface interaction, and material response modeling. These effects are strongly coupled both in representative ground test and flight environments; and an analysis of the sensitivity of their various components to one another is an active research area (not addressed here). A primary factor that limits the elucidation of detailed sensitivity relationships is the lack of test data to validate the various physical models. Ground test hypersonic facilities, although extremely useful, are limited in the fidelity with which they reproduce true flight environments. Turbulent transition phenomena, for example, which may increase heating rates by five- to ten-fold, cannot be simulated in any long-duration hypersonic facility. The conservative recourse, for a mission in which transition is suspected, is to design for the fully turbulent case and suffer the resulting mass penalty.

Currently, confidence in the ability to simulate untested entry environments depends on the success of modeling the closest corresponding environment for which test data exists, whether from ground facilities or flight. Even the most advanced physics-based models depend to some extent on varying parameters to achieve a best fit. The available data, however, simply do not yet allow critical tests of simulation tools over widely varying environmental parameters. As models are extended further to simulate new environmental and entry conditions, uncertainties are propagated over larger variable ranges.

Aeroshell failure is a single-point failure mode during entry. Our ability to predict the probability with which that event could occur is defined by the uncertainties carried in our aerothermal simulation and material response tools. For aeroshell failure mechanisms, such as burn-through, bond-line overheating, and excessive ablation, these uncertainties can be large because the data needed to quantify and reduce them is not available. The data provided by flight instrumentation would reduce those uncertainties and thus reduce mission risk for every subsequent mission.

Typically, the TPS design for any vehicle would employ a suite of materials to tailor the TPS solution to the anticipated heating environment for a region of the vehicle. A successful material will maintain its integrity at the temperatures induced by surface heating, and will maintain the temperature of its structural attachment surface (bond line) below a specified temperature. Surviving peak heating requires both a material that is sufficiently stable to withstand the induced temperature and a physical mechanism to reduce the induced temperature. Such mechanisms include radiative cooling, convective cooling, and ablation. Maintaining the bond line temperature requires that the bulk material be sufficiently insulating to prevent the total surface-deposited heat from diffusing to the back surface. The insulating ability is a function of the TPS thickness and the time-averaged heat flux, a quantity (heat load) derived by integrating the time history of the instantaneous heat flux. Time-resolved measurements of instantaneous heat flux, heat load, in-depth temperature (including bond line temperature), surface pressure, and surface recession (where appropriate) are critical tests of both aerothermodynamic and material response modeling tools. *These are the parameters that we propose to quantify through an evolved instrumentation system based on existing flight hardware.*

SENSOR TECHNOLOGY

New sensor technology allows lighter sensors and miniaturized sensor electronics that can be embedded into the TPS material. The distributed embedded system allows a cluster of sensors to be processed by a single, small embedded electronics module. The silicon germanium (SiGe) technology can provide electronics that operate at high temperature, up to the tolerance of the bonding material (260^{o} C.). Of particular interest is the development of embedded pressure transducers. These embedded sensors and electronics would reduce cabling weight and provide local a-to-d and multiplexing to simplify data collection. Thus, a larger number of sensors could be included in the TPS material of the heat shield.

The following embedded TPS engineering instruments are of interest:

1) Thermocouples
2) Recession sensors
3) Pressure transducers
4) Spectrometers
5) Heat flux sensors
6) Accelerometers

RECOMMENDATIONS

We recommend that NASA support the effort to develop an aeroshell flowfield and heatshield response instrumentation system using a mix of existing and new technology that will result in reduced risk and mass.

Providing engineering flight instrumentation in TPS for each entry mission will provide flight verification of theoretical models partially validated by ground testing. This will allow updating of the fluid dynamics, gas phase chemistry, and solid state physics models used for simulation to provide more accurate modelling of the next generation of entry vehicles. **We recommend** that NASA place **Level 1** requirements (on flight missions that have entry vehicles) to instrument the TPS of those vehicles for the benefit of all future Agency wide atmospheric reentry flight vehicles.

REFERENCES

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