Saturn Atmospheric Structure Investigation: An assessment of and Challenges and Recommendations for Extending the Galileo Approach to Future Probe Missions: E. Venkatapathy[1], D. Ellerby[2], D. Prabhu[3], and E. Martinez[2]; [1]Bldg 229, Rm 110, NASA ARC, Moffett Field, CA 94035, ethiraj.venkatapathy-1@nasa.gov., [2] NASA ARC, Don.Ellerby@nasa.gov,[3]dinesh.prabhu@nasa.gov,ERC, Inc.,

Summary: This paper provides a review of the methodology developed and applied by Seiff, et al. in constructing the upper atmospheric thermal structure of Jupiter's atmosphere from the Galileo Probe entry data. An assessment is made as to the challenges for extending not only the technique but also the applicability of the ARAD sensor. Recession measurement of the heat shield TPS obtained during Galileo probe entry was relied upon to deduce the upper atmosphere temperature structure. Although the methodology is applicable for future Saturn or Uranus probe missions, a number challenges are identified and explored. The following questions are analyzed from a Saturn mission perspective: 1) The effect of entry environment of Saturn probe and the applicability of ARAD sensor, 2) the choice of TPS and its implication to the fidelity of estimating mass loss, 3) Applicability of TPS sensor suite MISP flying on MSL to Saturn and 4) ultrasonic thermometry, a new development in sensor technology, applicability for TPS mass loss estimation.

The time of flight will be considerably longer for Saturn due to substantially large atmosphere. Use of recession sensors data may not correlate well with mass loss, depending on the choice of the TPS. In order to construct an accurate upper atmosphere thermal profile, high fidelity estimate of the mass loss is needed and we discuss how this can be achieved. Measurement of the mass loss of the ablative TPS requires an assessment of the entry profile, determination of the char as well as recession as a function of time. Advances in sensor development based on ultrasonic techniques, if matured and integrated with the recently developed MISP TPS sensor, some of these concerns could be easily addressed. The ultrasonic thermometry, a new, non-intrusive measurement technique and its development and integration with a new family of ablative TPS are discussed in a companion paper. We recommend an integrated sensor suite based on MISP on MSL and ultrasonic thermometry for Saturn atmospheric structure investigation.

Introduction: Saturn (and Uranus) Probe missions were identified as high priority missions by the NRC Decadal Survey Committee in its report " Visions and Voyages for Planetary Science in the Decade 2013-2022" [1]. Mission studies performed in support of the Survey identified determination of the atmospheric structure as a high priority scientific objective. The NRC Council identified a number of scientific questions, especially related to the thermal structure, in order to understand the atmospheric dynamical processes, heat flow and radiation balance for all the outer planets and more importantly for Saturn. Some of the relevant questions identified are: 1) what are the current pressure-temperature profiles? 2) Why and how does the atmospheric temperature and cloud composition vary with depth and location on the planet? 3) Which processes influence the atmospheric thermal profile, and how do these vary with location? and 4) What mechanism has prolonged Saturn's thermal evolution? [1]

Atmospheric structure investigation (ASI) is designed to obtained direct measurement of the pressure, temperature, etc. once the science probe is deployed and free of interference from heat shield. No direct measurement of pressure, temperature or density can be measured at upper reaches of Saturn when the probe entry is at speed close to 28 km/s and the hypersonic shock layer prevents direct measurement. The challenge of determining the upper atmospheric structure was first solved by Al Seiff. Al Seiff developed and applied the method for determining the thermal Structure as well as the pressure-temperature relationship of Jupiter's upper atmosphere from the mass loss of the heat shield determined via recession measurement during Galileo Probe entry. This technique is well described in Ref. [2]. The following paragraph is extracted from Ref [2].

"During entry, the probe heat shield was ablated by radiative and convective heating from the shock-layer plasma. Sensors embedded in the heat shield measured the surface recession as a function of time, and were used to calculate changes in probe mass and frontal area as functions of time. The density of the atmosphere was derived from probe decelerations through Newton's second law and the defining equation for drag coefficient,

$$D = (1/2)(\rho V^2)C_D A = ma \quad \text{--------------}(1)$$

Here, D is the aerodynamic drag on the probe; ρ, the atmosphere density; V, the probe velocity; CD, its drag coefficient; A, the frontal area, m, the probe mass; and a, the deceleration. Probe velocity was determined as a function of time by integrating the measured probe decelerations. Pressure is obtained from the density profile with the assumption of hydrostatic equilibrium. Temperatures were derived from these pressures and densities and the equation of state, $P =$ rRT. The gas constant, R, varies with altitude according to a composition model, which defines atmospheric mean molecular weight as a function of altitude. At the start of descent, density calculated from pressure and temperature measurements agreed closely with the final density from the entry profile, demonstrating small density uncertainty." [2]

In the case of ablators, mass loss is a sum of recession mass loss as well as losses due to change in density of the remaining TPS as a result of the pyrolysis decomposition process. Depending on the local temperature and pressure, virgin material is converted to charred material and the decomposition results in generation of pyro-gas which passes through the charred region to mix with external flow.

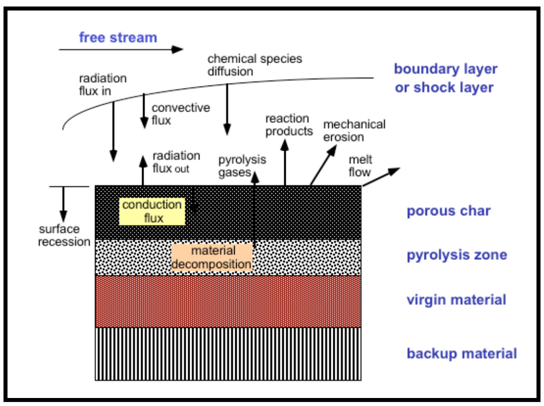


Fig. 1 Energy accommodation mechanisms of ablative TPS materials.

In some cases, the carbon in the pyrolysis gas may be deposited during it passage through the char region and increase the density of the char and this is knows as coking. For example, Apollo heat shield experienced coking. As a result, the char layer was substantially denser and the recession was substantially reduced during flight. The coking phenomenon is not very well understood as it is very difficult to simulate in ground test facilities (arc jets). The reason for this is that flight heating profiles are very different than arc jet test profiles and it is hypothesized that a thick char layer is a pre-requisite for the Coking to happen. So, understanding the physics and chemistry of the ablative TPS is essential.

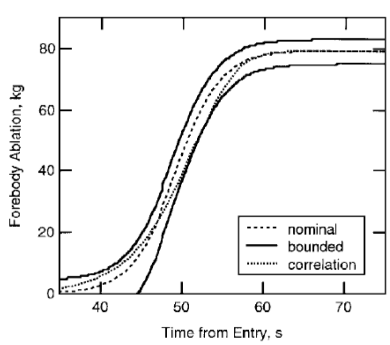


Figure 3. Forebody ablative mass loss history (Ref 3)

Galileo entry producedone of the most entreme entry heating and the recession that resulted in ~50% of the heatshield occurred within ~20 sec. Recession on the Galileo probe was measured by ten analog resistance ablation detector (ARAD) sensors installed in the forebody heat shield at six locations.

In addition to the complexities of the ablation physics, understanding what exactly the recession sensors measures and how it is translated to mass loss is important. An ARAD sensor is a three-terminal electrical device that produces a voltage proportional to the length of the sensor.

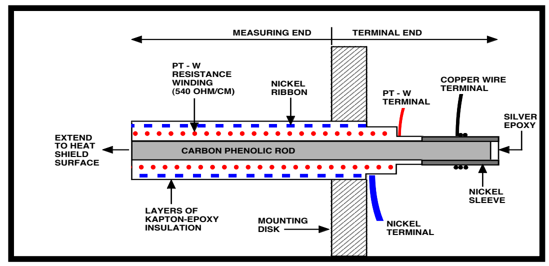


Figure 2. Analog Resistance Ablation Detector (ARAD) Design. (reproduced from Ref 3.)

As shown in Fig. 2, the sensor contains three coaxial electrically conductive components: an inner carbon phenolic rod, a closely wound helical coil of platinum-tungsten wire, and a outer winding of nickel ribbon. Kapton® tape and epoxy are used to insulate the conductive elements [3]. If the sensor tip is heated to suficiently high temperature (above 800–900 K), the Kapton and epoxy layers pyrolyze to form a tenacious, conductive char that completes a circuit for electric current to pass through the ARAD.

The ARAD data in reality corresponds to an isotherm between (800 K– 900 K). In ablative materials, especially those with pheolic resin system such as the heritage carbon phenolic used as the TPS material on the Galileo Aeroshell, the pyrolysis process of decomposition begins at a temperature range of (650 K– 700 K). When the heatflux is very high, the pyrolysis zone is realtively small and the recession and pyrolysis front propagate at a uniform rate. As a result, the ARAD sensor though it follows an iso-therm, tracks the recession at high heatflux . The resultsof arc-jet testing of ARADs in the Giant Planet Facility confirmed this for the Galileo Probe, which showed ARAD data accurately measuring recession up to a maximum recession rate of 0.1 cm/s.

Modernized version of the ARAD recession sensors are flying on the Mars Science Laboratory aeroshell. These sensors are integrated with thermocouple and seven such plugs are integrated on the PICA heatshield. PICA is also a TPS material that is made of carbon and phenolic but the manufacturing process of making PICA is very different than that of heritage, fully dense carbon phenolic that protected Galileo aeroshell. The HEAT sensor construction and the HEAT sensor integrated in the MISP plugs are shown in the figures below.

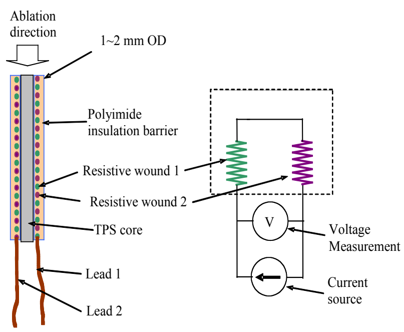


Figure 4. HEAT is a recession sensor similar to but modernized version of the ARAD sensor [3]

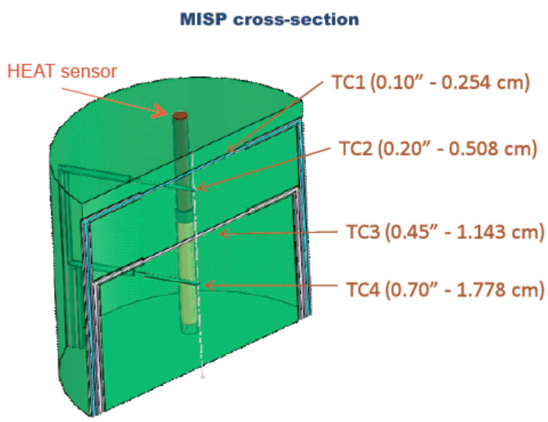


Figure 5. MISP (MEDLI Integrated Sensor Package) plugs incorporate both recession and thermocouple sensors into a single plug [3]

PICA being a low density ablalor capable of withstanding peak heatfluxes ~ 1000 W/cm^2. MSL peak heatflux is most likely less than 250 W/cm^2 and combined with the lifting entry of MSL will result in relatively small recession with significant charring of the ablator. The MISP sensor is calibrated to provide recession as well as char region as a result of two independent measurements within a co-loacted plug. The MISP plug on a PICA TPS for the MSL mission is a case study for designing a mass loss measurement for Saturn probe missions.

On heat shield ablative TPS material selection and sensor integration: Heritage carbon phenolic is no longer available due to the precursor rayon (Avtex) not manufactured since 1986. Future mission proposals have to baseline an alternate to heritage carbon phenolic. Recent upheavels in carbon due to termination of Space Shuttle Orbiter and delay in the development of Space Launch System by NASA are continuing to impact the sustainability of the manufacturing processes and alternate carbon phenolic is becoming risky. It is not clear if the carbon phenolic manufactruign is sustainable in the longer term or not. Recently NASA held a two day workshop entitled " Carbon Phenolic and Beyond" to address these concerns. The possible options are the use of nozzle grade rayon in conjunction with heritage processing to manufacture a Carbon Phenolic close to heritage. The conclusion from the workshop was that while alternate carbon phenolic is the least risky and possibly faster to manufacture in the near term, alternate TPS approaches, such as Woven TPS, might be able to be matured to meet the future missions needs. NASA's Office of Chief Technologist is investing in ablative Woven TPS. While carbon phenolic robust, it is shown to be mission limiting as the use of carbon phenolic makes the missions to lean towards higher G'load entry trajectories. Where as, the woven TPS, due to its tailorable nature, can be designed not to limit but to allow entry trajectories much shallower.

Note that once a TPS is selected, the ARAD or HEAT sensor design integration requires modification of the sensor. In figure 2, the central core of the ARAD sensor was carbon phenolic and this is to ensure that the ARAD sensor is thermally compatible with the ablative TPS namely carbon phenolic. If the base line TPS is changed, then the ARAD or HEAT sensor need to be redesigned to ensure compatiablity. For alternate forms of carbon phenolic, we do not believe this is going to be a challenge. Since the Woven TPS is in early stages of development, this has yet to be demonstrated if one chooses to use ARAD or HEAT sensor integration challenges are unknown at this time and it may or may not pose a challenge

So, depending on the TPS selection and also the entry heating pulse, the thermal response characteristics can be different. Next we address how different Saturn entry trajectories could be compared to Galileo and the challenges for recession (or mass loss) measurement.

Saturn Mission: A number of mission studies have been carried out in the past decade and the published results including the study performed by JPL in support of the Decadal Survey were analyzed for this paper. The lower gravitational acceleration produces larger atmospheric scale heights at Saturn. The shallower gravity well of Saturn compared to Jupiter results in reduced entry speeds {1}, as low as 26 km/s compared to the minimum of ~47 km/s at Jupiter, and this yields significantly smaller entry heating rates.

The larger atmospheric scale heights at Saturn, on the other hand, results in longer time of flight and a heat-load comparable to that of Galileo Probe entry into Jupiter. The Saturn Probe Trade Studies performed by Rita Bebe and her team [5] concluded the following: "Entry into Saturn's atmosphere from hyperbolic approach to the Saturn system involves intense heating, but that heating is still nearly an order of magnitude less intense than a similar entry into Jupiter's atmosphere. The aerothermal environment requires carbon phenolic for the heat shield's Thermal Protection System (TPS), but under conditions well within the carbon phenolic performance envelope; it would not require the enhanced performance needed for the Galileo Probe, where entry conditions were at the upper edge of that envelope. Notably, at entry speeds (relative to the atmosphere) of 30 km/s or less, TPS and heat shield performance could be tested using existing facilities. The ~27 km/s entry speed of a Saturn probe falls within this limit, so use of the Galileo Probe's heritage carbon phenolic is not required. Carbon phenolic currently being manufactured for use in solid rocket motor nozzles might be used instead." In Appendix C of the above reference [5], the authors provide a detailed discussion and compare Saturn Probe with Galileo probe design.

Lower peak heating but longer time of flight and comparable heat-load necessarily means, the recession and char layer progression need not be in sink. This means use of the ARAD sensor alone may not result in accurate estimate of mass loss. So, the question is how can the mass loss estimate for Saturn be improved?

MSL entry profile and the choice of PICA as the TPS material is relatable to Saturn entry profile with a high performance and moderate-to-high density ablative TPS choice (the choice to go with either non-heritage carbon phenolic or an alternat Woven TPS that is more efficient and enabling is not assumed at this time). In case, the ablative TPS material on the heatshield does not behave similar to Galileo TPS, then in order to accurately estimate the mass loss, we need the following: (1) Need to measure recession either directly or indirectly, (2) need to know the boundary between virgin and char, and (3) need to know the density variation within the pyrolysis zone and (4) need to know where the boundary between the pyrolysis zone and the char. The MISP plug provides better information from which we can determine the above four zone to a degree, depending on the number of thermocouples. Thermocouples are notorious for not able to withstand high temeperatures as they burn out.

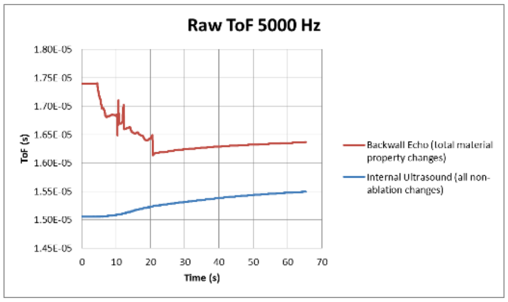
Alternate approaches to measure Recession and Density Variation in a TPS: A a new, innovative, non-intrusive ultrasonic instrumentation under developmnet for measuring recession of the ablative TPS during atmospheric entry is described in a companion paper. Non-intrusive ultrasonic ablation and temperature distribution measurement offers the promise of real-time information. Ultrasound can transform a heat shield itself into a sensor while observing recession and recession rate, internal temperature distribution, and in some cases heat flux. While ultrasonic sensors have flown in heat shields in the past[4], modern signal processing and localization methods have been developed to combine the technologies of ultrasonic thickness gauging and ultrasonic thermometry into a method of temperature compensated recession measurement, with the side effect of temperature distribution measurement.

Ultrasonic thermometry is a non-intrusive technology that incorporates the structure being monitored as part of the sensor methodology. Ultrasonic sources embedded into or attached to the backside of a heat shield can be used to measure ablation, temperature, and heat flux. Thermal response times on the order of 100 microseconds (without thermal lag) can be attained [4]. Diffuse ultrasonic backscatter from a material's microstructure can be monitored at selected regions within a material and converted to temperature[5,6]. The data from regions that do not ablate can be used to directly compensate for temperature and material property changes at the surface without modeling.

The ultrasonic thermometry application to measuring recession and in-dpeth temperature as well predicting density variation is currently under development by IMS Inc. (see the companion paper for more details). To illustrate what is possible, a 3-D woven carbon-phenolic ablative TPS was tested in an arc jet and the ultrasonic thermometry was used to measure time-of-flight sound propagation and by post-processting the signal, the recession was predicted. Figure 6. illustrates the current efforts obtained in a laboratory setting with the Woven TPS that is potentially suitable for Saturn missions.

Our Recommended Approach: For the case of Saturn, our recommendations are to develop an integarted approach to measure recession, and char layers using independent measurements.

MISP plug with an integrated HEAT sensor for the appropriate TPS material, once it is baselined, using the same approach as that of MISP developement for PICA) and also develop Ultrasomnic thermometry and integrate the two into a single package. Ultrasonic thermometery is very promising to measure the recession front whereas neither ARAD nor HEAT sensor can measure recession directly. Though ultrasonic thermometry is a promising approach, density variation may not be easy to obtain but could be interpreted from the HEAT sensor and also from thermocouple readings. Hence, our recommendation is to construct an integrated instrumentation that leverages the MSL MISP plug design and the non-intrusive ultrasonic thermometry into a single package and start the technology maturation of such as system along with the ablative TPS material technology maturation.



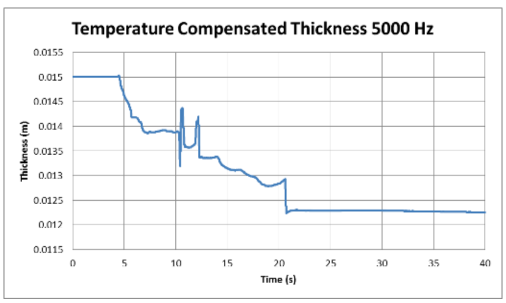


*Figure 6.*a) Raw data collected from ultrasound on a 3-D Woven TPS from the receding surface and internal microstructure, (top) and b) that same data converted directly to thickness without a model (bottom).

Concluding Remarks: Saturn probe missions is a high priority science objective recommended by the NRC PSDS 2013-2022**.** One of the important scientific goal is to construct the atmospheric structure, especially the thermal profile for Saturn from the recommended Probe mission. While the methodology developed by Al Seiff is applicable to Saturn, by revisting the ARAD sensor approach, we see a number of challenges. Our receommedation is for a integrated development of a sensor based on MSL MISP sensor plug combined with a non-intrusive ultrasonic thermometry. MISP approach will need to be developed first for the ablative TPS of choice and the integration of the ultrasonic thermometry can be narrowly focused on the direct measurement.

References: *[1] Committee on the Planetary Science Decadal Survey, (2011) National Academies Press. [2] Seiff, A., et al. (1997) Science 276, 102. [5] Bebe, R. and Dudzinski, L., "Satrun Atmospheric Probe Trade Studies,"[2011], NASA Web Publication, http://ia600507.us.archive.org/31/items/SaturnAtmosphericEntryProbeTradeStudy/19_Saturn-Probe-Trade-Studies.pdf, [3] Munk, M., "Application of the MEDLI suite to Future Mars Entry Vehicles," presented at the Concepts and Approaches for Mars Exploration workshop (2012), [4]McGunigle R. D. and Jennings M. (1975) International Instrumentation Symposium Proceedings, 12, 19–24. [5] Yuhas D. E. et al. (2009) American Institute of Physics QNDE, 28B, 1759-1766. [6] Simon C. et al. (1998) IEEE Trans. on Ultrasonics, Ferroelectric and Frequency Control, 45(4). [7] Amini A. N. (2005) IEEE Trans. Biomed Eng., 52(2), 221-228.*