DEVELOPMENT OF A SOLID STATE THERMAL SENSORS FOR AEROSHELL TPS FLIGHT APPLICATIONS

Ed Martinez[1], Tomo Oishi[2], Sergey Gorbonov[3]

[1] NASA Ames Research Center, Moffett Field CA 94035
[2] Ion America, Moffett Field CA 94035
[3] ELORET Corporation, Moffett Field CA 94035

1. INTRODUCTION

In-situ Thermal Protection System (TPS) sensors are required to provide verification by traceability of TPS performance and sizing tools. Traceability will lead to higher fidelity design tools, which in turn will lead to lower design safety margins, and decreased heatshield mass. Decreasing TPS mass will enable certain missions that are not otherwise feasible, and directly increase science payload. NASA Ames is currently developing two flight measurements as essential to advancing the state of TPS traceability for material modeling and aerothermal simulation: heat flux and surface recession (for ablators). The heat flux gage is applicable to both ablators and non-ablators and is therefore the more generalized sensor concept of the two with wider applicability to mission scenarios.

This paper describes the continuing development of a thermal microsensor capable of surface and in-depth temperature and heat flux measurements for TPS materials appropriate to Titan, Neptune, and Mars aerocapture [1,2], and direct entry. The thermal sensor is a monolithic solidstate device composed of thick film platinum RTD on an alumina substrate. [3,4] Choice of materials and critical dimensions are used to tailor gage response, determined during calibration activities, to specific (forebody vs. aftbody) heating environments. Current design has maximum operating temperature of 1500K, and allowable constant heat flux of q=28.7 W/cm^2, and time constants between 0.05 and 0.2 seconds. The catalytic and radiative response of these heat flux gages can also be changed through the use of appropriate coatings. By using several co-located gages with various surface coatings, data can be obtained to isolate surface heat flux components due to radiation, catalycity and convection. Selectivity to radiative heat flux is a useful feature even for an in-depth gage, as radiative transport may be a significant heat transport mechanism for porous TPS materials in Titan aerocapture.

2. TEST RESULTS IN A FOREBODY TPS APPLICATION

In December 2003 a series of arc jet tests (Table 2.2) were conducted to evaluate thermal microsensor performance mounted in-situ in a 3-inch diameter blunt cone model of Fibrous Reinforced Ceramic Insulation (FRCI-12 (Shuttle tile) coated with RCG. The test series exposed 5 models to cold wall heat fluxes of 42 and 60 W/cm2 in 13 total exposures. This configuration of tile and coating is extremely well characterized as it is used for Shuttle acreage TPS. The configuration replicates a forebody heatshield application where the sensors were mounted on a plug [Fig 2.1], and inserted from behind into the model. A top view picture of 5 different models can be seen in Fig 2.2. The sensors were mounted 1/16 inch below the surface of the coating, and a thermocouple was mounted 0.01 inches below the thermal sensor to provide a comparison. The objectives of this test series were to demonstrate the ability to record RTD data during an arc jet run; demonstrate thermal shock survivability beyond 900 C of the sensors; obtain sensor performance versus independent measurements; and, obtain data on performance limits (T, delta-T, Q, and Q-dot). This was the first test series which used the thermal microsensors with TPS in an arc jet test. All objectives were met with complete success, as demonstrated in the data below.

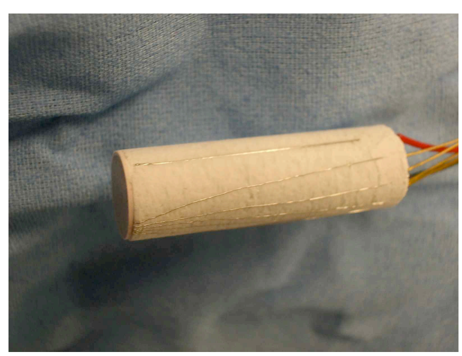

Fig 2.1. Thermal Sensor Plug

Fig 2.2. Blunt Cone Models

Model Name	Sensor location Depth [in]	# of runs	Date	Duration (sec)	Cold Wall Heat flux (W/cm^2)	Sensor current (mA)
S1	1/16	4	12/04/03	128	41.3	1
			12/08/03	183	60.5	1
			12/18/03	169	59.6	10
			12/18/03	167	60.4	15
S2	1.468	1	12/04/03	30	41.3	1
S3	0.3	2	12/05/03	302	42.2	1
			12/08/03	242	41.0	1
S4	1/16	4	12/05/03	303	42.2	1
			12/08/03	136	41.0	1
			12/18/03	168	59.6	10
			12/18/03	140	60.4	20
S5	0.3	2	12/05/03	304	42.2	1
			12/08/03	243	60.5	1

Table 2.2. Arc Jet Test Series for Heatshield simulation

A material response simulation was performed at NASA Ames using the Fully Implicit Ablation and Thermal Response Simulation Code (FIAT). The predictions and data presented in Figs. 2.3 and 2.4 are for 42 W/cm^2 and 60 W/cm^2 cold wall heat flux, respectively. Figure 2.3 shows the comparison of in-depth heat flux history between prediction and the thermal sensor reading. The in-depth heat flux is calculated at 0.1587 cm (1/16") below the surface, where the sensor is located. As seen in the graph the comparison is excellent. The peak heat fluxes match within 5%, and the shapes of the curves almost overlay. The transition at 400 seconds happens when the model is removed from the arc jet flow, at this point the surface temperature is much higher than the surrounding environment and heat radiates away from the model instead of into it, as seen from 100 to 400 seconds. Also important is the almost overlay of the calculation and measurement of the return to baseline from 400 to 1400 seconds. This is a strong indicator that the sensor is functioning correctly with no baseline or calibration shifts. This is the first known direct measurement of heat flux in-situ of a TPS material.

A comparison of temperature between the thermal sensor and the thermocouple mounted 0.01 inches below the thermal sensor can be seen in Fig 2.4. As seen by the dashed lines the peak temperatures are within +/-2%, and within +/-5% on the cold soak after the model is removed from the arc jet stream. A similar result is seen for a different test at the higher heat flux of 60 W/cm2 in Fig 2.5. These experimental comparisons between a traditional method of the thermocouple versus the thermal microsensor verifies the ability of the sensor to make accurate long duration temperature measurements to at least 1000 C. Figure 2.6 shows the repeatability of the heat flux measurements for 4 different tests at 60 W/cm2. These results are typical for all 13 exposures.

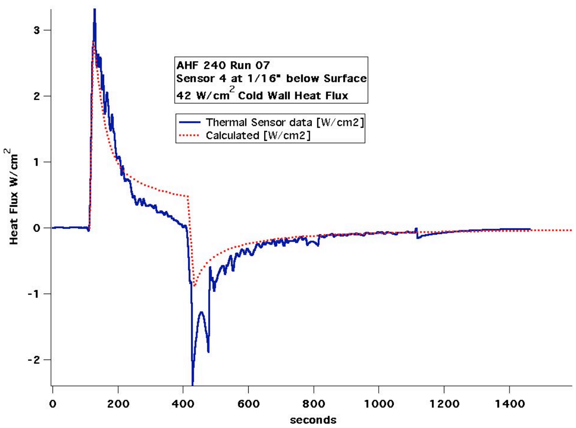

Figure 2.3. In-depth heat flux (42 W/cm^2)

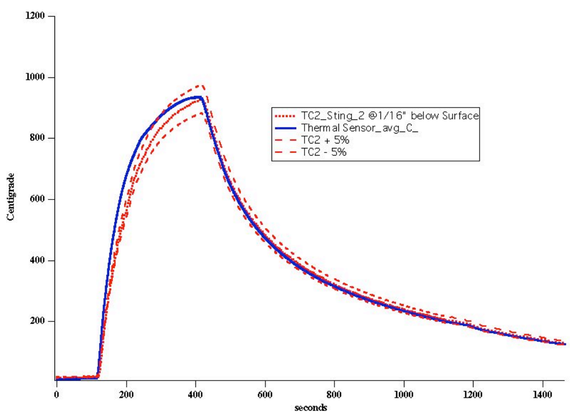

Fig 2.4. In-depth temperatures at 42 W/cm^2

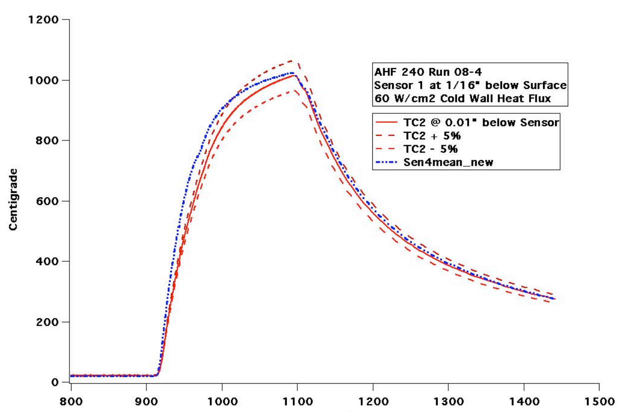

Fig 2.5. Comparison of in depth temperatures at 60 W/cm^2

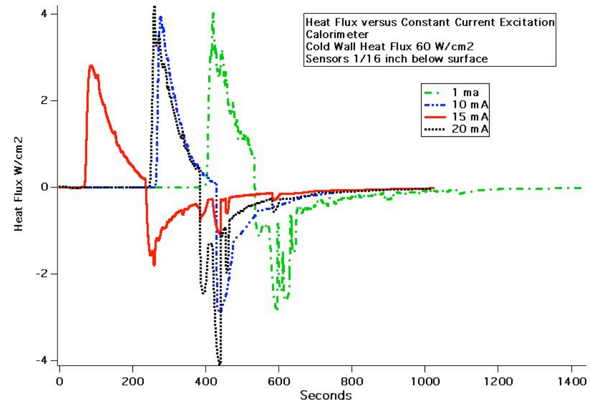

Fig 2.6. Repeatability of in-situ heat flux at 60 W/cm^2

3. TEST RESULTS IN AN AFT SHELL APPLICATION

Pre and post-dictions were performed using the FIAT code. The measured surface heat flux, using a foil calorimeter (Gardon gage) [5,6] was used as the input for the FIAT computation. To match the measured maximum surface temperature of 725 C at t = 254 sec, the input maximum heat flux was scaled to 5.7 W/cm^2. Figure 2.7 presents the comparison between computation and data at the model surface and bond-line. The predicted temperature profiles (symbols) generally agree with TC data. However, the sensor temperature reading (colored in black) responds as expected versus the thermocouple data. When the materials get close to steady state conditions both the sensor and material temperatures converge, as seen in the plot.

This is due to the mismatch in diffusivity between the ceramic thermal barrier and the low-density silica tile. Also, there are significant differences in emmisivity between the sensor (_ ~ 0.3) and the uncoated tile (_ ~ 0.5), causing temperature variations between the two as energy is reradiated away from the surface of each. This is an example of the data necessary to calibrate response specific to materials, locations, and times of interest during reentry.

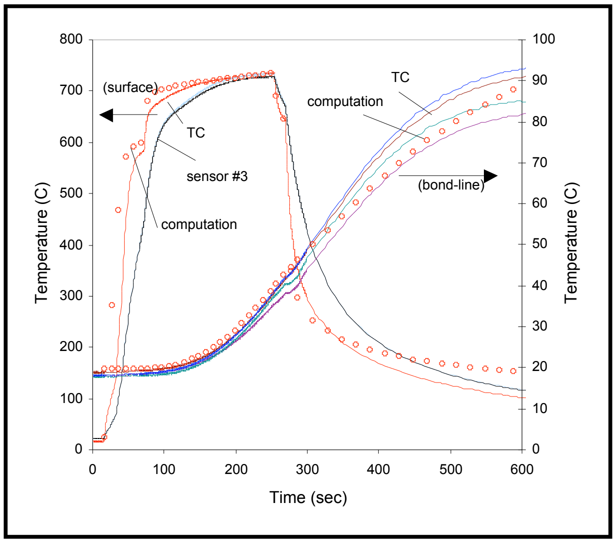

Figure 2.7. Comparison between prediction and TC data

4. Conclusions

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 against 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).

5. REFERENCES

[1] Wercinski, P.F., Henline, W., Tran, H., Milos, F., Papadopoulos, P., Chen Y.K., and Venkatapathy, E., "Trajectory, Aerothermal Conditions, and Thermal Protection System Mass for the Mars 2001 Aerocapture Mission," AIAA Paper 97-0472, January 1997.

[2] Throckmorton, D.A., "Benchmark Determination of Shuttle Orbiter Entry Aerodynamic Heat Transfer Data," *Journal of Spacecraft,* v. *20, p. 219-224, 1983.*

[3] Noltingk, BE (ed.) Instrumentation Reference Book, Butterworths & Co. Ltd. London, 1988.

[4] Julian W. Gardner, "Microsensors: principles and applications," Wiley, 1994.

[5] Gardon, R., ''An Instrument for the Direct Measurement of Intense Thermal Radiation," *Rev. Sci. Instrum*., 24, No. 5, pp. 366–370, 1953.

[6] Jones T V "The thin film heat transfer gauges - a history and new developments," *4th National UK Heat Transfer Conf., Manchester* (London: ImechE) pp 1–12, 1995.

[7] Simmons S G, Hager J M and Diller T E, "Simultaneous measurement of time-resolved surface heat-flux and free stream turbulence at a stagnation point," *Heat Transfer* v. 2, ed G Hetsroni (New York: Hemisphere), 1990.