

INSTRUMENTATION FOR MEASURING ENTRY RADIATIVE HEATING – PAST, PRESENT, AND FUTURE. R. A. Miller¹, T. R. White², G. T. Swanson², A. M. Brandis¹, and B. A. Cruden¹, ¹AMA Incorporated at NASA Ames Research Center, ²NASA Ames Research Center.

Introduction: Radiative heating can be a significant contributor to the total heat load during atmospheric entry, especially for large vehicles with high entry velocities [1-4]. For example, the stagnation region heat load derived from thermocouples embedded in the thermal protection system (TPS) of the Mars Science Laboratory (MSL) heatshield did not match the unmarginated pre-flight predictions. This was at least partially attributed to the fact that radiative heating was not accounted for in the unmarginated pre-flight predictions [2]. Since MSL, significant work has been done to update radiative heating models and test how the models perform compared to ground-based test facilities such as shock tubes. The models and ground-based tests have shown that radiative heating can be significant for entry into the atmospheres of Venus, Earth, Mars, and Titan, among other planetary bodies [1-4]. However, there are still discrepancies between the models and the test data, which is where the desire for flight data comes in to play. Missions that have had or are currently planned to have instrumentation to measure radiative heating during atmospheric entry are listed in Table 1 [5-19].

State-of-the-Art Instrumentation: There are two main types of radiative heating instrumentation: radiometers and spectrometers. Radiometers measure the integrated radiance within a specific wavelength range within their field of view. Radiometers can be further classified as either broadband or narrowband based on their measured spectral range. Radiometers are relatively simple instruments (generally consisting of a window and a heat flux sensor), have a small foot-print, are straight forward to calibrate, often don't require external power, can have high sensitivity, fast time response, low data volume, and wide field of view. Some of the drawbacks/limitations of radiometers include greater difficulty in validating radiative heating models, since they do not measure spectral radiance, and blockage of signal due to ablation product redeposition on the window or in the cavity.

Spectrometers measure the spectral radiance within a specific wavelength range by using optical gratings and mirrors paired with a detector such as a photodiode array. Spectrometers, similar to radiometers, require an optical port in the TPS, but spectrometers also require a connection (such as a fiber optic) between the optical port in the TPS and the spectrometer itself. Spectrometers have more complex calibration processes, require external power, have high data volume, and based on

the current technology are wavelength limited from ultraviolet to near infrared for flight applications due to fiber optic and detector material constraints (i.e. transmission and temperature constraints). The large benefit provided by spectrometers is that they make spectrally resolved radiation measurements enabling direct comparison to model predictions.

Scope of the Presentation: This presentation will discuss why flight radiative heating measurements are important and will examine the current state-of-the-art instrumentation being implemented on missions such as Mars 2020, LOFTID, and Artemis. Additionally, areas of technology development to address limitations in the current state-of-the-art will be proposed and implementation of radiative heating instrumentation on future entry flight missions will be recommended.

References: [1] Cruden B. A. and Brandis A. M., 16th IPPW, 2019. [2] Cruden B. A. et al., *Journal of Thermophysics and Heat Transfer*, 30, 642-650, 2016. [3] Brandis A. M. and Cruden B. A., 47th AIAA Thermophysics Conference, 2017-4534. [4] Johnston C. O. and Brandis A. M., *Journal of Spacecraft and Rockets*, 52, 105-119, 2015. [5] Woollard B. A. et al., IEEE Aerospace Conference, 2016. [6] Richardson, N. R. NASA TN-D-3646, 1966. [7] Keafer L. S., Jr. and Burcher E. E., NASA TN-D-4937, 1968. [8] Ried, R. C., Jr. et al., NASA TM-X-58091, 1972. [9] Seiff, A. et al. *Icarus*, 18, 525-563, 1973. [10] Erdman P. W. et al., *Journal of Thermophysics and Heat Transfer*, 7, 37-41, 1993. [11] Erdman P. W. et al., *Journal of Thermophysics and Heat Transfer*, 7, 704-708, 1991. [12] Cruden B. A. and Johnston C. O., 46th AIAA Thermophysics Conference (ITAR Restricted), 2016-4113. [13] Gülhan A. et al., *Journal of Spacecraft and Rockets*, 56, 68-81, 2019. [14] Morgan J. et al., AIAA Aerospace Sciences Meeting, 2018-1234. [15] Bailet G. et al., 11th IPPW, 2014. [16] Hwang H. et al., 46th AIAA Thermophysics Conference, 2016-3536. [17] Swanson G. et al., 15th IPPW, 2018. [18] Wright M. et al., 16th IPPW, 2019. [19] Brandis A. et al., 17th IPPW (Submitted), 2020.

Table 1. Missions with Entry Radiative Heating Instrumentation

Mission	Year	Planet	Sensor Type(s)	Sensor Location(s)
FIRE I	1964	Earth	3 Broadband Radiometers	Stagnation Point, Forebody, Backshell
			1 Scanning Radiometer	Stagnation Point
FIRE II	1965	Earth	3 Broadband Radiometers	Stagnation Point, Forebody, Backshell
			1 Scanning Radiometer	Stagnation Point
Trailblazer II	1965	Earth	2 Radiometers	Stagnation Point
Apollo 4	1967	Earth	4 Broadband Radiometers	Stagnation Point, Forebody, Backshell
Apollo 6	1968	Earth	4 Broadband Radiometers	Stagnation Point, Forebody, Backshell
PAET	1971	Earth	9 Channel Narrowband Radiometer	Forebody
BSUV	1990	Earth	1 Scanning Spectrometer	Forebody
			8 Photometers	Forebody
BSUV 2 (UVDE)	1991	Earth	1 Scanning Spectrometer	Forebody
			8 Photometers	Forebody
EFT-1	2014	Earth	2 Broadband Radiometers	Stagnation Point, Leeside Forebody
ExoMars Schiaparelli	2016	Mars	1 Broadband Radiometer	Backshell
			3 Pairs of Narrowband Radiometers	Backshell
SASSI2 CubeSat	2019	Earth	1 Spectrometer	Forebody
QARMAN CubeSat	2020	Earth	1 Spectrometer	Forebody
Mars 2020 MEDLI2	Launch 2020 Entry 2021	Mars	1 Broadband Radiometer	Backshell
Artemis 1	2021	Earth	2 Broadband Radiometers	Forebody
LOFTID	2022	Earth	1 Broadband Radiometer	Rigid Nose
Artemis 2	2022	Earth	2 Spectrometers	Forebody
			1 Broadband Radiometer	Backshell
Dragonfly	Launch 2026 Entry 2034	Titan	1 Broadband Radiometer (Preliminary)	Backshell (Preliminary)