3D Material Response of the MSL Heatshield Using NuSil-Coated PICA

Jeremie B.E. Meurisse[1], Georgios Bellas Chatzigeorgis[1], Brody Bessire[2], Dinesh Prabhu[1] and Nagi N. Mansour[1]
[1]Analytical Mechanics Associates Inc. at NASA Ames Research Center and [2] NASA Ames Research Center

IPPW-2021, July
Analytical Mechanics Associates (AMA) Inc.

Introduction and development of the PICA-NuSil model

The Mars Science Laboratory (MSL) Entry, Descent and Landing Instrumentation (MEDLI) collected in-flight data largely used by the ablation community to verify and validate physics-based models for the response of the Phenolic Impregnated Carbon Ablator (PICA) material [1-4]. MEDLI data were recently used to guide the development of NASA's high-fidelity material response models for PICA implemented in the Porous material Analysis Toolbox based on OpenFOAM (PATO) software [5-6]. A follow-up instrumentation suite, MEDLI2, was used for the Mars 2020 mission [7] after the large scientific impact of MEDLI. Recent analyses performed as part of MEDLI2 development drew the attention to significant effects of a protective coating to the aerothermal response of PICA. NuSil, a silicone-based overcoat sprayed onto the MSL heatshield, including the MEDLI plugs, as contamination control, is currently neglected in PICA ablation models. To mitigate the spread of phenolic dust from PICA, NuSil was applied to the entire MSL and Mars 2020 heatshields, including the MEDLI and MEDLI2 plugs. Ground testing of PICA-NuSil (PICA-N) models exhibited surface temperature jumps due to oxide scale formation and subsequent NuSil burn-off. It is therefore critical to include a model for the aerothermal response of the coating in ongoing code development and validation efforts. Figure 1 illustrates the PICA-N model implemented in PATO with a test case that shows a temperature jump and a change of recession rate at the wall after 20 seconds of simulation when the NuSil coating was fully removed.

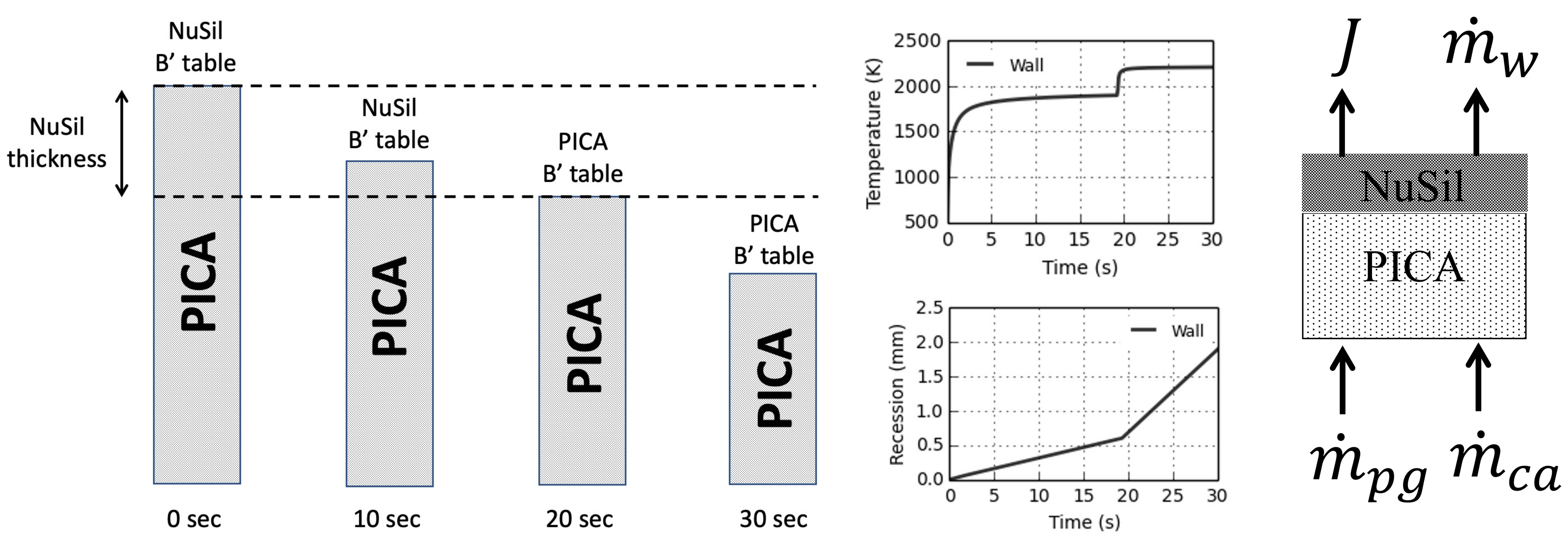

Fig. 1 Description of the PICA-NuSil model implemented in PATO showing the wall temperature jump, the change of wall recession rate and the surface mass balance.

Surface model of PICA-NuSil using equilibrium chemistry

In this work, the material response model of PICA-N is presented and the effect of NuSil is analyzed. The charred NuSil surface is modeled as pure silica (SiO_2) based on the observations of a glassy layer on the post-test coated samples. Equations (1) and (2) describe the surface mass balance for multiple elements at the wall. Figures 2 and 3 compare the dimensionless char blowing rate (B_c') and the wall enthalpy (h_w) between carbon and silica surfaces in Mars atmosphere. B_c' is proportional to the surface recession rate, while h_w has an impact on the wall temperature, as described in the surface energy balance (Eq. (3)).

$$C_{\mathrm{M}}(z_{k,\mathrm{w}} - z_{k,\mathrm{e}}) + z_{k,\mathrm{w}}\,(\dot{m}_{\mathrm{ca}} + \dot{m}_{\mathrm{pg}}) = \dot{m}_{\mathrm{pg}}\; z_{k,\mathrm{pg}} + \dot{m}_{\mathrm{ca}}\; z_{k,\mathrm{ca}} \quad (1)$$

$$B_{\mathrm{c}}' = \frac{\sum_{l=1}^{N_{\mathrm{el}}^{\mathrm{s}}} \left[B_{\mathrm{g}}'\,(z_{l,\mathrm{pg}} - z_{l,\mathrm{w}}) + z_{l,\mathrm{e}} - z_{l,\mathrm{w}}\right]}{\sum_{l=1}^{N_{\mathrm{el}}^{\mathrm{s}}} (z_{l,\mathrm{w}} - z_{l,\mathrm{ca}})} \quad (2)$$

$$\left[-\underline{\underline{\mathbf{k}}} \cdot \partial_x T\right] \cdot \mathbf{n} = q_{\mathrm{diff}} + \dot{m}_{\mathrm{ca}}(h_{\mathrm{ca}} - h_{\mathrm{w}}) + \dot{m}_{\mathrm{pg}}(h_{\mathrm{pg}} - h_{\mathrm{w}}) + q_{\mathrm{rad}} \quad (3a)$$

$$q_{\mathrm{diff}} = C_{\mathrm{H}}'(h_{\mathrm{e}} - h_{\mathrm{w}}) \quad (3b)$$

$$q_{\mathrm{rad}} = \alpha_{\mathrm{w}} q_{\mathrm{pla}} - \varepsilon_{\mathrm{w}}\sigma\left(T^4 - T_{\infty}^4\right) \quad (3c)$$

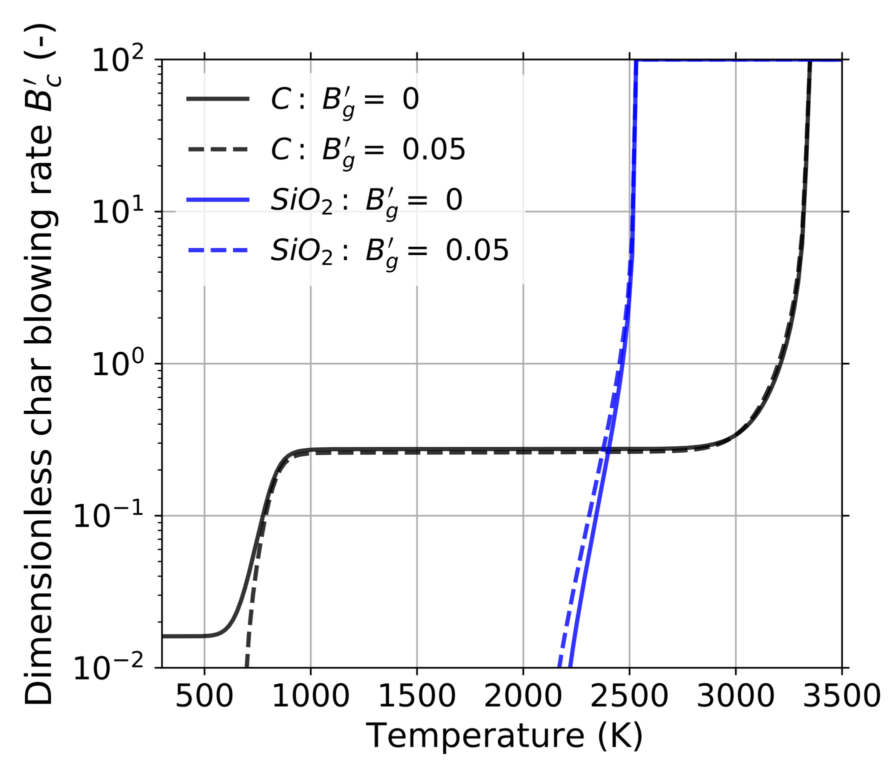

Fig. 2 B_c' in function of temperature for carbon and silica surfaces (Mars).

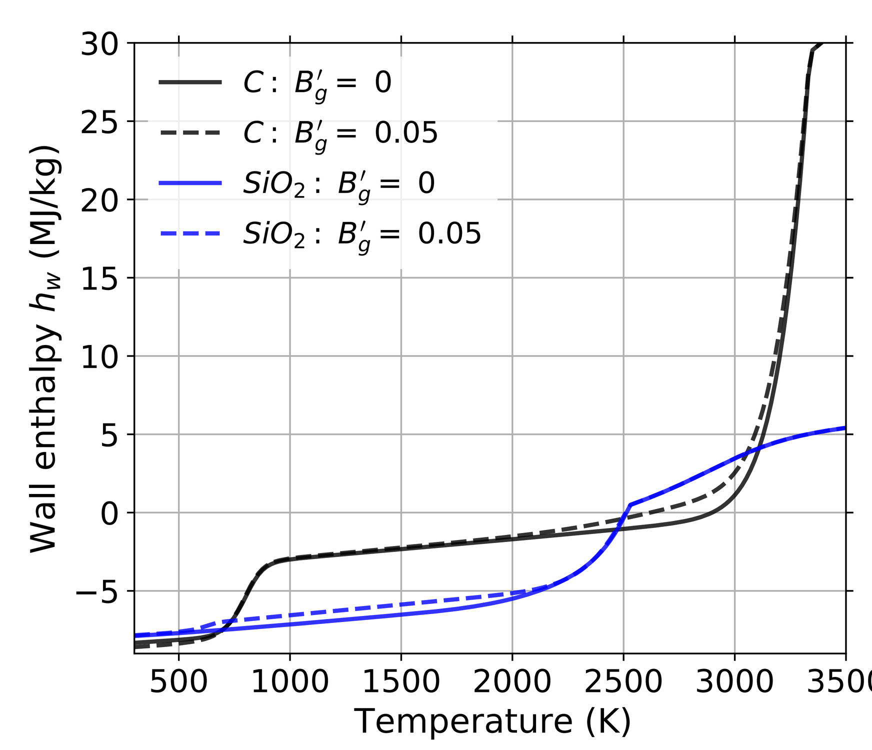

Fig. 3 h_w in function of temperature for carbon and silica surfaces (Mars).

3D simulations of the MSL heatshield using the PICA-NuSil model compared to MISP flight data

The computational model implemented in PATO is a generic mass and heat transfer model for porous reactive materials, where each control volume contains several solid phases and a single gas phase. The detailed chemical interactions occurring between the solid phases and the gas phase are modeled at the pore scale assuming local thermal equilibrium. A novel model of PICA-N has been developed at NASA using experimental data from multiple NASA arc-jet test campaigns and has been implemented in PATO [8]. 3D simulations of the MSL heatshield were performed using the NASA Supercomputer to compare PICA and PICA-N models with the MISP flight data. The fully turbulent aerothermal environment was computed in the Data Parallel Line Relaxation (DPLR) code [9]. The NuSil layer thickness on top of PICA was estimated to be 200 μm in these simulations. Figure 4 compares the thermal response of the MSL heatshield front surface between PICA and PICA-N models at 80 sec after Entry Interface (EI). The PICA-N model gave lower surface temperature results than the PICA model. Figure 5 shows the surface recession of the MSL heatshield at 80 sec after EI showing higher recession results for the PICA model. According to the PICA-N model, the NuSil coating still fully covers the MSL heatshield at 80 sec after EI. Figure 6 depicts the time evolution of the temperature for PICA and PICA-N models at the MISP-2 location. In a fully turbulent environment, both models overpredict the in-depth temperature compared to the measurements from the MISP-2 flight data.

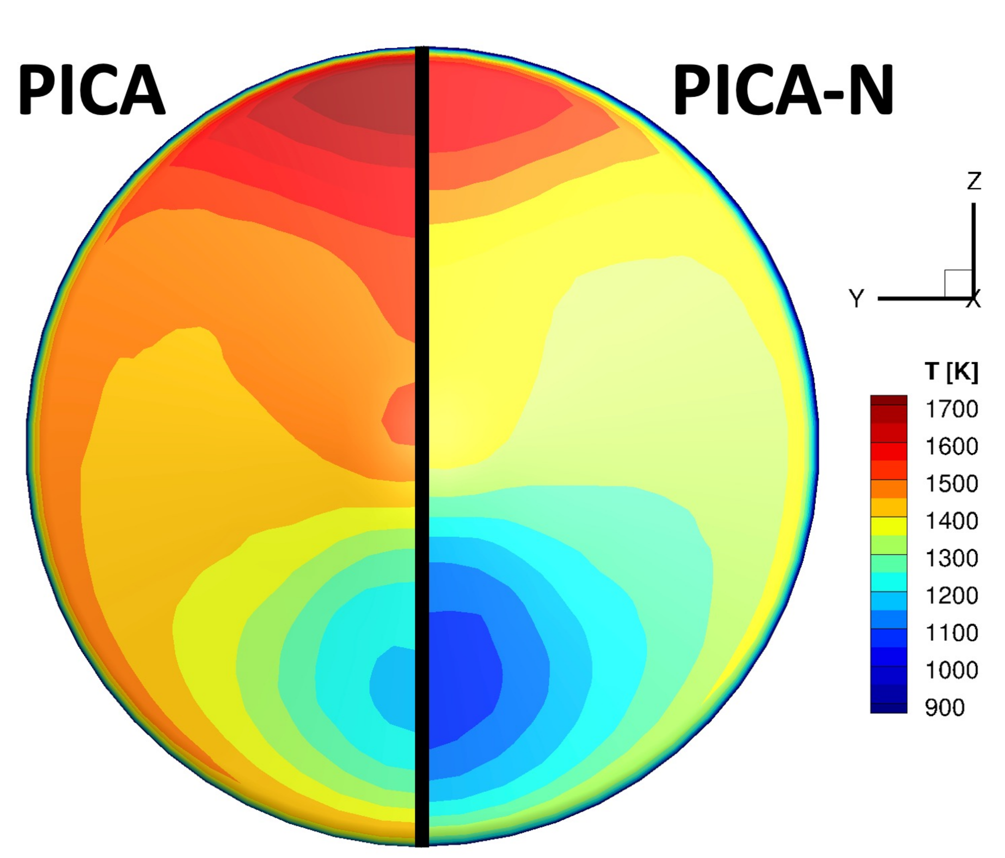

Fig. 4 Surface temperature of MSL using PICA (left) and PICA-N (right) models at 80 sec after EI.

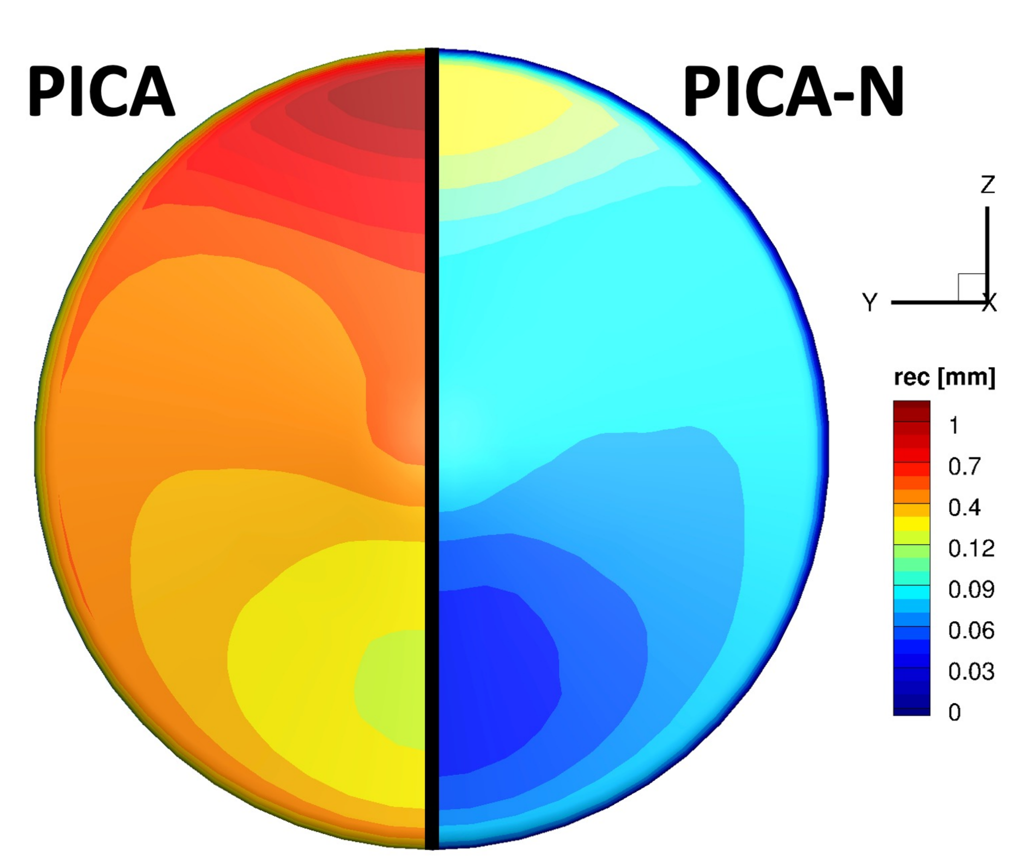

Fig. 5 Surface recession of MSL using PICA (left) and PICA-N (right) models at 80 sec after EI.

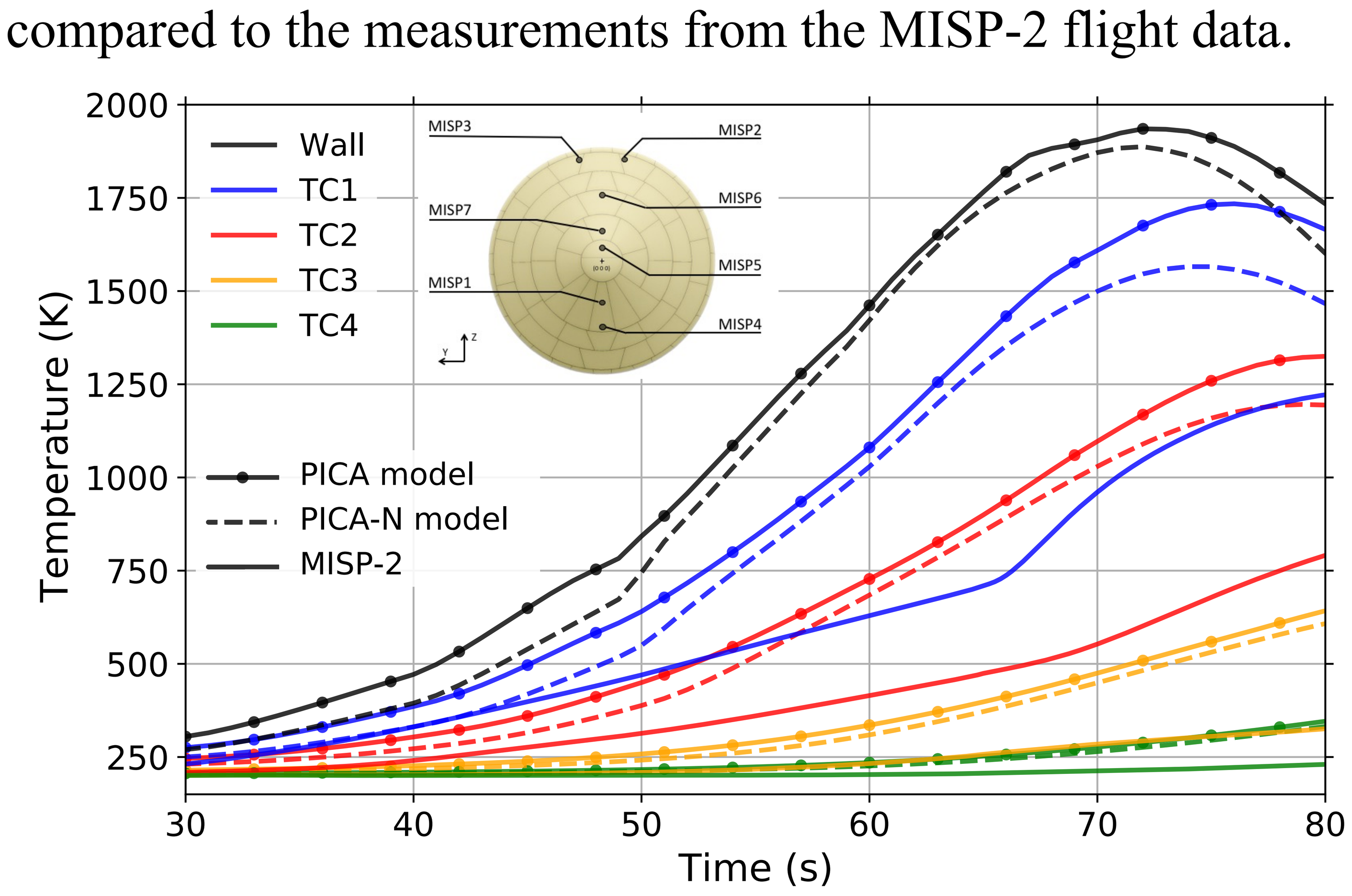

Fig. 6 Temperature profile of the PICA and PICA-N models compared to the MISP-2 flight data.

References

[1] D. Bose *et al.* (2013), *51st AIAA Aerospace Science Meeting*.
[2] M. Mahzari *et al.* (2013), *51st AIAA Aerospace Science Meeting*.
[3] D. Bose *et al.* (2014), *Journal Spacecraft Rockets*.
[4] M. Mahzari *et al.* (2015), *Journal Spacecraft Rockets*.
[5] J. Lachaud *et al.* (2017), *Int. Journal of Heat and Mass Transfer*.
[6] J. Meurisse *et al.* (2018), *Aerospace Science and Tech. Journal*.
[7] H. Hwang *et al.* (2016), *46th AIAA Thermophysics Conference*.
[8] J. Meurisse *et al.* (2019), *11th Ablation Workshop*.
[9] M. J. Wright *et al.* (1998), *AIAA Journal*.