

## Finite-Rate Ablation and Oxide-Layer Models for Reentry Spacecraft

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### Abstract

Reentry spacecraft experience extreme heating and surface chemistry that heatshield materials must withstand or that can lead to the demise of spacecraft materials and release of product species into the atmosphere. A common assumption made in such analysis is equilibrium surface chemistry. While this may be accurate for carbon recession rates under certain conditions, it does not accurately predict product species. Furthermore, equilibrium surface chemistry is likely not accurate for oxide layer growth and volatilization, which involve slower chemical reactions compared to carbon oxidation. For these reasons, finite-rate ablation and oxide layer models are needed that are accurate over a wide range of temperatures and pressures experienced by reentry spacecraft materials.

Recently, molecular beam experimental data was used to create the finite-rate air-carbon ablation (ACA) model [1]. By explicitly including surface coverage effects, the model captures the non-Arrhenius trend for CO production versus increasing temperature and also introduces pressure dependence. New comparisons between CFD simulations using the ACA model and recent carbon ablation experiments will be presented [2]. Next, a reformulation of the ACA model will be presented that can predict ablation of various forms of carbon by two controlling parameters; the number of available reactive sites and the ratio of strongly-to-weakly bound oxygen on the surface. The new ACA model formulation is compared to new molecular beam data for HOPG, vitreous carbon, and graphite materials.

Modeling oxide layer formation and volatilization is important for reusable hypersonic materials and also for predicting the demise spacecraft. Some thermal protection systems form silica-based oxides and most metals will form complicated oxides when exposed to oxygen at high temperature. Previous modeling has mainly used equilibrium chemistry approaches, however, the time history of the oxide layer may be important as its growth and/or volatilization occurs on timescales comparable to trajectory variations. We therefore implemented the finite-rate model of Fertig et al. [3] into the US3D CFD code and verified against prior test case results. New results will be presented that demonstrate finite-rate oxidation layer formation in a high-enthalpy reactive air flow. Both finite-rate models (carbon ablation and oxide layer formation) and the coupling to CFD tools may be useful for predicting the demise behavior of carbon-based materials and oxide-layer-forming materials upon reentry.

[1] Prata, K.S., Schwartzentruber, T.E. and Minton, T.K., “Air–Carbon Ablation Model for Hypersonic Flight from Molecular-Beam Data”, *AIAA Journal*, 60(2), pp.627-640, 2022.

[2] McClernan, P.G., Schroeder, O.M., Fagnani, A., Knutson, A.L., and Schwartzentruber, T.E., "Finite-Rate Modeling of Air–Carbon Ablation in a Plasma Wind Tunnel, " *JTHT*, Vol. 40, No. 2 (2026), pp. 323-336 doi: doi/abs/10.2514/1.T7237

[3] Fertig, M., Herdrich, G., and Auweter-Kurtz, M., “SiC Oxidation and Catalysis Modelling for Re Entry Heating Predictions,” *European Space Agency, (Special Publication) ESA SP*, Vol. 659, Jan. 2009

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