Investigations of High-Temperature Oxygen-Carbon Ablation by Molecular Beam-Surface Scattering

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Abstract

An end-of-life scenario for the demise of a LEO satellite might start with deceleration from drag, followed by heating, ablation, and breakup as the satellite descends into the dense atmosphere. Some key physical and chemical processes would be gas-surface energy transfer, ablation reactions on high-temperature surfaces, and pyrolysis of polymeric materials. We have used molecular beam methods to provide insight into all these processes, yet this presentation will focus on the findings of many molecular beam-surface scattering experiments to gain an understanding of the high temperature (1000 – 2000 K) atomic-oxygen-induced ablation of model carbon materials. Earlier molecular beam data were used as the basis of an air-carbon ablation model (generally referred to as the "ACA model"), but refinement of this model was needed to make it more applicable to a variety of carbon types and environments. Thus, new molecular beam experiments have been conducted to expand the range of carbon materials studied, and the new data have been provided to inform an update of the ACA model in the group of Prof. Tom Schwartzentruber at the University of Minnesota.

The new experiments were performed with pulsed molecular beams of O atoms. The reactive scattering dynamics of O on various carbon surfaces – vitreous carbon (revisited), HOPG, isostatically-molded graphite (IMG), and a 3D carbon-carbon composite (C/C) – suggest that the oxidation mechanisms on all sp^2 types of carbon are similar but that the morphology of the surface region strongly influences the relative importance of the individual mechanisms. The relative probabilities of the observed gas-surface interactions, both reactive and non-reactive, were quantified as a function of surface temperature. Carbon surfaces that have lower density or more porosity tend to exhibit higher reactivity. In addition to reacting with carbon to produce CO_2 (minor product) and CO (major product), unreacted O atoms may scatter through thermal and non-thermal processes, and, with sufficiently high incident O-atom flux, O-O recombination on the surface to produce O_2 may occur with an efficiency that is somewhat lower than that to produce CO. Furthermore, O atoms may be retained through adsorption on the surface or absorption into the bulk, leading to slow production of CO on a timescale of tens of microseconds to hundreds of milliseconds. The slow processes through which CO is formed and released from the surface may account for as much as half the CO that is produced at lower temperatures, whereas the slow production of CO becomes negligible at higher temperatures and all the CO is released within a few microseconds of O-atom impingement on the surface. Relative to vitreous carbon, IMG and C/C show broader temperature ranges over which slow thermal release of CO remains important. The molecular beam scattering results indicate the importance of microstructure in the temperature-dependent ablation rate of carbon by atomic oxygen. The results further show that slow CO production, on a timescale up to hundreds of milliseconds, should be considered in experiments and models where the finite rate of oxygen-carbon ablation may be important.