

HIGH TEMPERATURE EMISSIVITY OF METEORITES AND THE RELATIONSHIP TO ABLATION RATES. D. R. Ostrowski^{1,2} and J. B. Haskins^{1,3}, ¹NASA Ames Research Center, Moffett Field, CA, USA., ²Bay Area Environmental Research Institute, Ames Research Center, Moffett Field, CA, USA, ³Analytical Mechanics Associates, Ames Research Center, Moffett Field, CA, USA, E-mail: daniel.r.ostrowski@nasa.gov.

Introduction: Meteors have been bombarding Earth throughout history with most being small and burning up in the atmosphere. A few are large enough to survive entry and cause notable damage, for example flattened forest in Tunguska or injured people and property damage in Chelyabinsk, Russia [1,2]. Between ablation and other means most meteorites lose greater than 80% of their mass during entry [3].

Thermal properties are an important fundamental characteristic of the meteorites, an indicator of both their chemical and physical nature. The physical properties of the meteorites are needed to determine the likelihood of meteoroids survivability during atmospheric entry. The Asteroid Threat Assessment Project (ATAP) has been set up to investigate the full risk and outcomes that near Earth asteroids pose to the planet. One of the tasks of this program is to study the physical properties of meteorites that pertain to how a meteor behaves during atmospheric entry. Ablation models require the input of emissivity [4,5,6]. The emissivity of a meteorite has direct input to the time it takes for the surface material to reach melt temperatures.

Meteorites contain both high and low thermally conductive materials. For darkening material emissivity will increase as temperature increases until peak temperature is reached and then begins to decrease [7]. The metal components will slowly increase the emissivity as temperature increases, while the non-metallic material's emissivity will decrease. It has been determined for urelites that emissivity decreases as a function of temperature above 500K [7].

Experimental: Thermal emissivity for the selected meteorites has been measured over a broad wavelength range of 8 to 14 μm from $\sim 20^\circ\text{C}$ up to 600°C . Emissivity values for up to atmospheric entry temperatures are needed for modeling. For lower temperatures the emissivity is measured at 15°C increments, 50°C increments for intermediate temperatures, and 100°C increments at higher temperatures. For Sikhote-Alin emissivity is measured at temperatures up to 1000°C to cover both phase transitions of kamacite. Emissivity is measured by dual laser infrared thermometers with accuracy 1% of measured temperature $\pm 1^\circ\text{C}$. With the infrared temperature gun set to an emissivity of 1, the temperature of both the sample and a black body are measured. In these experiments the black body is a titanium cube coated in carbon black high temperature

paint. The ratio of the meteorite temperature to the blackbody temperature is calculated as the emissivity.

Surface temperature simulations are performed with the Icarus material response solver, which is a fully implicit, parallel finite volume code, and a one-dimensional grid that represents the stagnation point on the surface of a large meteoroid. The surface is treated with an aerothermal boundary condition using the typical assumption of radiative equilibrium (i.e., emissivity is equal to absorptivity). Simulations of both iron meteoroids and ordinary chondrites are performed. The physical properties of meteoric iron and ordinary chondrites were approximated to be similar to those of pure iron [8] and an H5 chondrites examined by ablation experiments, [9] respectively. The accuracy of the emissivity from these datasets, which are referred to as heritage datasets, is a central question for meteor entry, where radiation is the primary means of heat transfer.

Results: All meteorites analyzed in this study have higher emissivities at 20°C compared to analog material. The average emissivity of ordinary chondrite falls and Antarctic meteorites at 20°C is 0.988 ± 0.008 . Other meteorite classes have similar emissivities at 20°C , as seen in Figure 1.

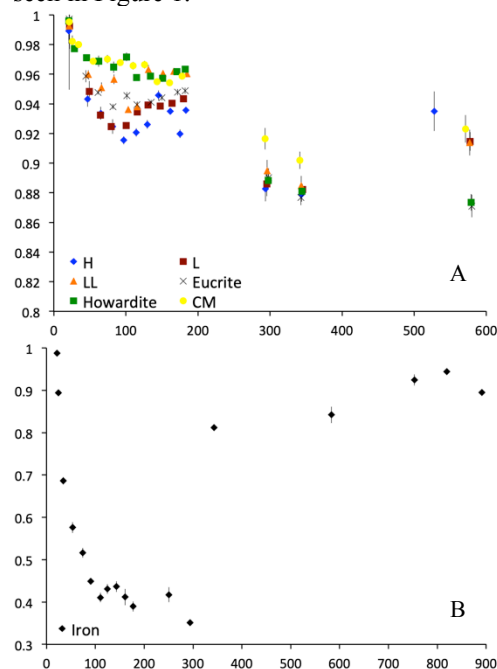


Figure 1. (A) Thermal emissivity profiles for stony meteorites. (B) Thermal emissivity profiles for iron meteorites.

Elevated temperatures cause a fluctuation in the emissivity of the different meteorite classes. As temperature increases to 100°C the emissivity decreases then rebounds and stabilizes for the next 100° (Fig. 1A). The rebound emissivity value for most of the chondrites is around half of the initial 100°C decrease. Lowest emissivity between 300-350°C, nearly all values below 0.90. Heated chondrites range in emissivity between 0.85-0.95. When comparing values between ordinary chondrite falls and Antarctic meteorites no notable differences are observed. Of the studied meteorite classes only the iron meteorites follow a drastically different emissivity profile as a function of temperature. This different profile is caused by the phase transitions in kamacite as heated. This only applies to the lower boundary. As seen from figure 1B, the upper phase transition in kamacite around 600°C.

Initial values of material temperature and radiative heat transfer rate are needed to perform material response simulations of meteor entry. The temperature of meteors in space is strongly dependent on the solar radiation flux and their optical properties. Such investigations indicate that iron and stony meteoroids have temperatures of roughly 350 and 261 K, respectively. The aerothermodynamic environment of meteors during entry has been examined on the basis of chemically reacting computational fluid dynamics coupled with radiation transport and surface ablation [10]. The radiative heat flux for a 10 m meteor with a 20 km/s velocity at 50 km was determined to be 7800 W/cm².

Material response simulations of surface heating during entry may be performed. To evaluate the influence of the temperature-dependent, solid optical properties on entry, the preheating stage of the meteor is evaluated (Fig. 2). The case of the iron meteorite (Fig. 2A) compares simulations using heritage iron optical properties to those performed with the values measured in the present work. The heritage values result in the surface temperature reaching the melting point (near 1800 K) within 0.2 s of entry. Use of the values measured in this work lead to the 2 time to melt being cut in half. The reduction in the time to melt is a result of the 0.5 increase in emissivity of the Sikhote-Alin sample above 600 K. Such an increase does not occur for pure iron. A simulation also has been carried out for an ordinary chondrite (Fig. 2B). The ordinary chondrite surface temperature increases to the melting point (near 1800 K) within 0.02 s. The heritage optical property dataset for ordinary chondrites is similar to that measured in the present work, exhibiting a maximum variation of roughly 0.1. Comparatively, the time to melt is slower in the iron meteor case due to higher thermal conductivity, which leads to the rapid transport of heat from the surface to the interior. The faster heating of the iron meteor surface is a result of the emissiv-

ity of meteoric iron being higher than that of pure iron at high temperatures and the establishment of radiative equilibrium at the surface.

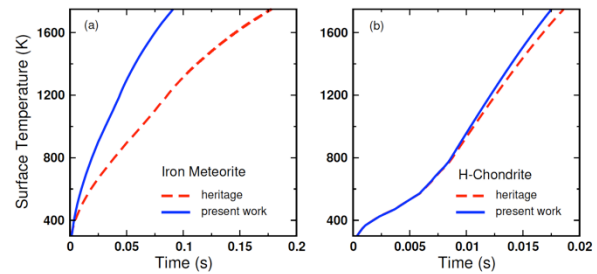


Figure 2. Material response modeling of the surface temperature of (A) an iron meteorite and (B) an H-chondrite as a function of exposure time to the radiation flux expected for a 10 m diameter specimen entering the atmosphere at 50 km. The profile is examined up to the approximate melting points of meteoritic materials (1800 K).

Conclusion: Thermal emissivity is a uniform trend across both ordinary chondrite falls and Antarctic finds. The emissivity profile of stony meteorites as temperature increases is similar with only a slight difference around 600°C. As for iron meteorites have a different emissivity profile caused by the kamacite phase change. The lower emissivity at elevated temperatures does affect the ablation rate by decreasing the time for the surface material to reach melt temperature. The most effected by this is the iron meteors, as seen in figure 2A, where the time to melt temperature is cut in half. The H chondrite meteoroids are less affected with only a 0.02 second increase.

Acknowledgments: This work was funded by NASA's Planetary Defense Coordination Office (PDCO) and is conducted under the Asteroid Threat Assessment Project at NASA Ames Research Center.

References: [1] Vasilyev N. (1998) *Planet. Space Sci.* 46, 129-150. [2] Popova O. et al. (2013) *Science*, 342, 1069-1073. [3] Sears D.W. (1974) *Thermoluminescence and Fusion Crust Studies of Meteorites*. University of Leicester. [4] Flynn G.J. (1989) *Icarus*, 77, 287-310. [5] Lyne et al. (1996) *JGR*, 101, 23,207-23,212. [6] Campbell-Brown M.D. et al. (2013) *Astronomy and Astrophysics*, 557, A41, 1-13. [7] Loehle S. et al. (2017) *Meteoritics & Planet. Sci.*, 52, 197-205. [8] Mills K.C. and Keene B.J. (1987) *Int. Mater. Rev.* 32, 1. [9] Agrawal P. et al. (2018) *Aerodynamic-Measurement Technology and Ground Testing Conference*. [10] Johnston C.O. et al. (2018) *Icarus*. 309, 25.