HIGH TEMPERATURE THERMAL CONDUCTIVITY OF METEORITES AND THE RELATIONSHIP TO ABLATION RATES. D. R. Ostrowski[1,2] and J. B. Haskins[1], [1]NASA Ames Research Center, Moffett Field, CA, USA., [2]Bay Area Environmental Research Institute, 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 thermal conductivity [4,5,6].

Meteorites contain both high and low thermally conductive materials. Most of thermal conductivity has been measured below 350K and shows that most meteorites have conductivity values of ~3W/mK or less [7]. Limited meteorites have been measured above 350K, but shows that thermal conductivity can exceed 4W/mK [8]

Experimental: Thermal conductivity for selected stony meteorites has been measured at six temperatures over the range of ~300K up to 850K. Thermal conductivity values for up to atmospheric entry temperatures are needed for modeling. The thermal conductivity is measured using a Unitherm model 2101 Comparative Cut-bar Thermal Conductivity meter. The comparative cut-bar method entails placing the sample of known size and shape between two identical standards of known size, shape, and thermal conductivity. Fused quarts cylinders of length 2.4 cm are used as standard. Meteorite samples used are 1.5cm in length. Holes are drilled near top and bottom of both standards and samples to allow thermocouples to be placed at the center of the material. Thermal conductivity is measured using equation 1:

$$k_s = 0.5\left[\frac{d_s}{A_s * \Delta T_s} * \left(\left(k_{tr} * \frac{A_{tr} * \Delta T_{tr}}{d_{tr}}\right) + \left(k_{br} * \frac{A_{br} * \Delta T_{br}}{d_{br}}\right)\right)\right]$$

where k is thermal conductivity, d is length of material, A is cross section area of material, ΔT is change of temperature across material, subscript s is sample, subscript tr is top reference, and subscript br is bottom reference.

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. Simulations of ordinary chondrites are performed. The physical properties of ordinary chondrites were approximated to be similar to those examined by ablation experiments [9].

Results: All meteorites analyzed in this study, except Chelyabinsk, have higher thermal conductivity values at 300K compared to basalt analog, ~1.5W/mK [10]. At 300K the bulk of meteorites have conductivity values much higher than granite, ~2.25W/mK [10], with their being five meteorites varying between granite and basalt. The range of Antarctic meteorites alone at 300K is 1.72±0.38 to 4.24±0.21W/mK.

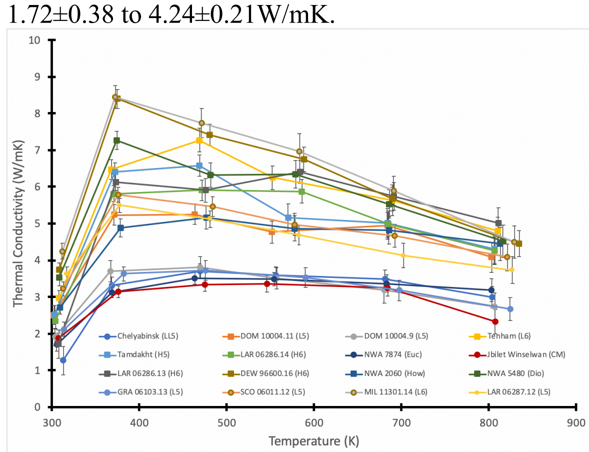

Figure 1. *Thermal conductivity profiles for stony meteorites.*

Two thermal conductive groups are formed among measured values once heated (fig 1). The initial profile of both groups is similar to results of enstatite chondrites where upon heating the thermal conductivity spikes ups and than slowly decreases as temperature continues to increase, but never down to the value of analog material at similar temperatures [8]. For the meteorites studied, except LAR 06286 (H6), the highest value of conductivity occurs at 375K. After this point for both groups, within error, the thermal conductivity for all meteorites remains constant or decrease as temperature increases. This trend is consistent with analog material of granite and basalt [10]. The two groups have different distinct shapes and slopes. The lower group is a tight packed set of meteorites with very uniform slope of nearly flat to slight negative over 375-825K range. While the upper group has wide rage of negative slopes from the flat, within error, howardite NWA 2060 to the rapid decline of MIL 11301 of 0.897±0.005W/mK per 100K. The variable rates of conductivity decrease do bring all upper group values between 4-5W/mK by 850K. It is possible to project out that by 1000K the upper and lower group would merge.

The types of meteorites in each group is composed of both ordinary chondrites and HED meteorites. Of the ordinary chondrites the H-type are only in the upper group, LL-type is in the lower group, and L-type chondrites are in both upper and lower groups. Iron content and porosity also have effect on which group a meteorite will be a member. As noted by the H chondrites that if a meteorite has a high iron content it will only be in the upper group. Both groups have high porosity meteorites, but porosity of 10% or less is only in the upper group.

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 stony meteoroids have temperatures of roughly 261 K. 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 [11]. The radiative heat flux for a 10 m meteor with a 20 km/s velocity at 50 km was determined to be 7800 W/cm^2.

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). Surface temperature increases to the melting point (near 1800 K) of Chelyabinsk within 0.02 s. The heritage is an average of optical property dataset for ordinary chondrites is similar to that measured in the present work, exhibiting a maximum variation of roughly 0.1. Of the heritage the thermal conductivity value is from calculated or modeled values at 275K. Comparation of the heritage and the new direct measured high temperature values shows no difference (Fig. 2). This suggested that initial surface heating is so great that a thermal conductivity increases of 1-2W/mK has negligible effect.

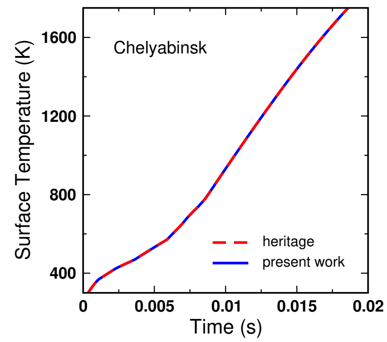

Figure 2. *Material response modeling of the surface temperature of Chelyabinsk (LL chondrite) as a function of exposure time to the radiation flux expected for a 10 m diameter specimen entering the atmosphere at 50 km. The profile is examined up to the approximate melting points of meteoritic materials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

Conclusion: Thermal conductivity of ordinary chondrite falls, Antarctic finds, and howardite/eucrite/diogenite finds are higher at all elevated temperatures than analog material. Thermal conductivity values increase from 300-375K and remain constant or decrease as temperature is increase. The thermal conductivity profile of stony meteorities at elevated temperatures forms two distinct groups. The lower group has constant or slightly decreasing conductivity with final values around 3W/mK. Meteorites with high iron or low porosity cannot be in the lower group. While the upper group has a wide range of decreasing thermal conductivity rates with all ending between 4-5W/mK.

Time to surface melt like conditions during atmospheric entry is not affected by the change in thermal conductivity values as temperature increases. This is most likely a result of heating being very intense rapidly.

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