Simulating Ordinary Chondrite Ablation at the Hypersonic Materials Environmental Test System

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I. INTRODUCTION

A test campaign was carried out at the Hypersonic Materials Environmental Test System (HyMETS) to investigate the dominant ablation mechanisms (e.g., vaporization, melt flow spray, and fracture) of an ordinary chondrite (Tamdakht – H5) and samples collected from the Columbia River Basalt (CRB) group.

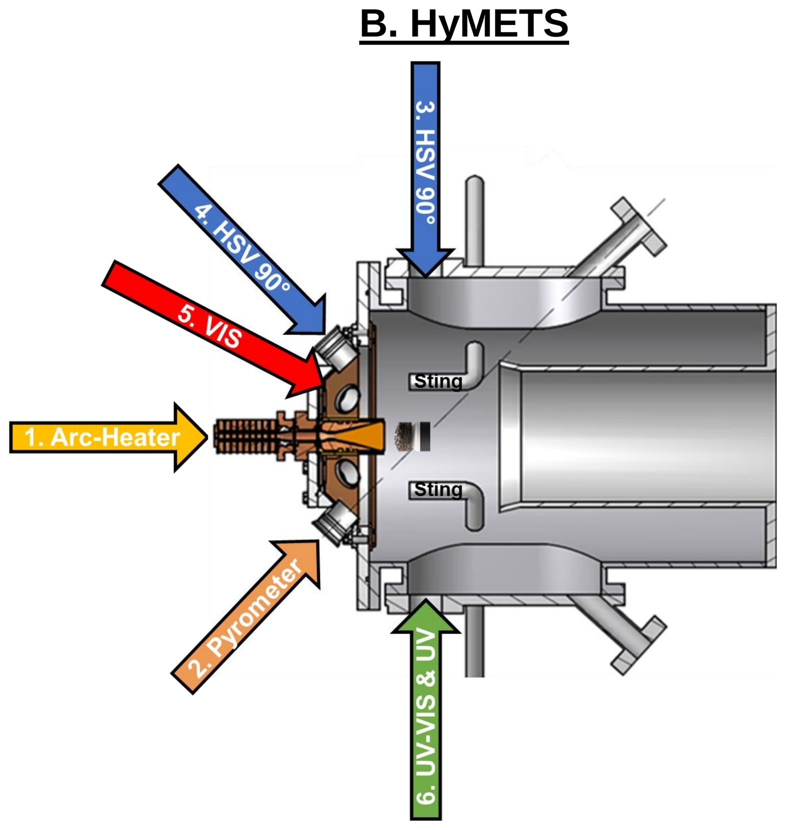
II. MATERIALS & METHODS

The HyMETS facility is a 400-kW constricted arc heater used to screen material performance under simulated aerothermal conditions of hypersonic flow.[1] Facility settings were chosen to simulate Earth entry conditions between the upper mesosphere and the lower thermosphere.

Test article assemblies were constructed from cylinders (Ø = 33 mm, ℓ = 20 mm) of the test target material (A. Tamdakht & Basalt), ceramic insert, and graphite sting adapter. Test assemblies were attached to a sting arm and subjected to a hypersonic flow of air plasma (B. 1) for seven seconds. Surface temperatures are measured with a two-color pyrometer (B. 2). High-speed videos were used to monitor salient ablation phenomena (B. 3 & 4). Finally, a suite of spectrometers were used to detect species emitting in the boundary layer and the stagnation surface of each test article (B. 5 & 6).

A. Test Articles

B. HyMETS



C. Test Conditions

Condition	Heat Flux / W cm^{-2}	Pressure / Pa
A	322	3051
B	285	7439

III. MATERIAL RESPONSE

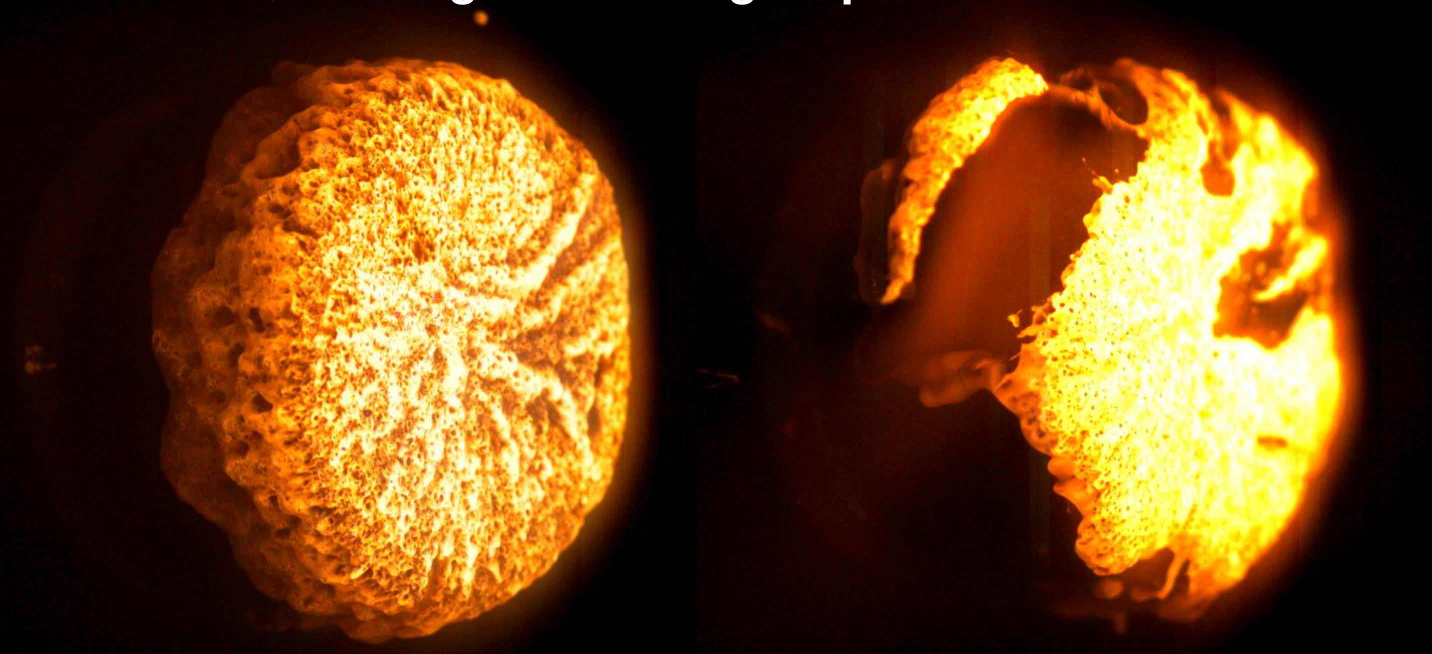
Images from High-Speed Video

- Tamdakht develops a stable melt flow as evidenced by the build up of a flange at the edge of the cylinder.
- Basalt loses large sections of the viscous melt layer and subsurface material into the flow.

	Tamdakht	Basalt
Recession Rates (mm s^{-1})	0.064	0.116
Mass Loss Rates (g s^{-1})	0.05	0.60

- Mass loss and recession rates indicate that basalt ablates more readily than Tamdakht.

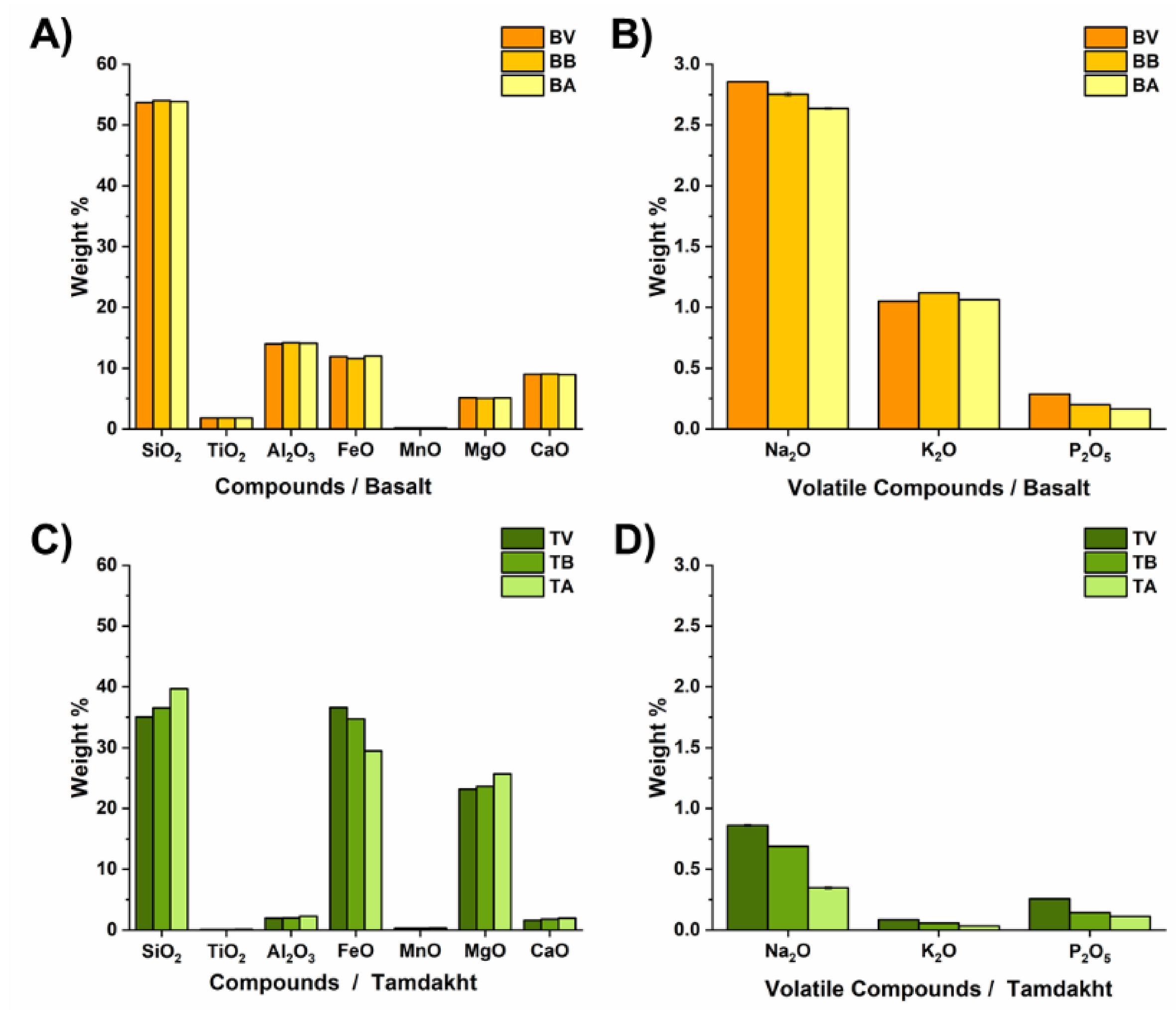
Images from High-Speed Video



TAMDAKHT BASALT

IV. POST-TEST ANALYSIS

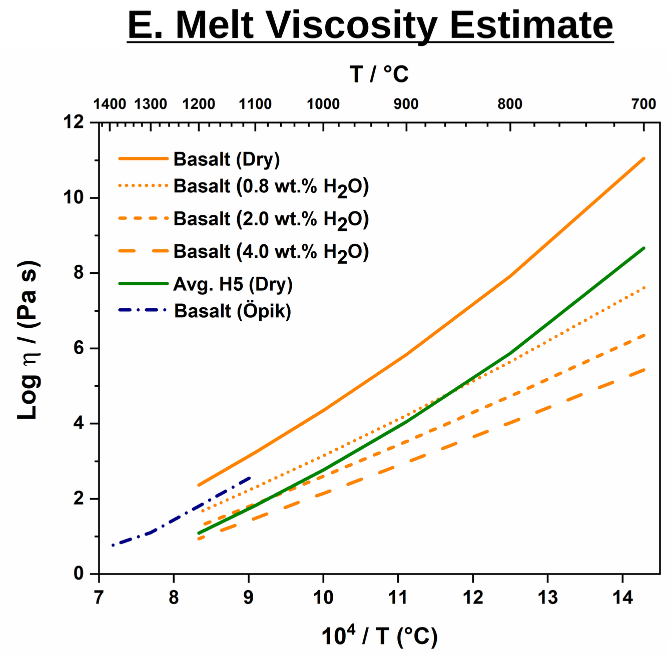
D. Post-Test Melt Layer Analysis (X-ray Fluorescence)



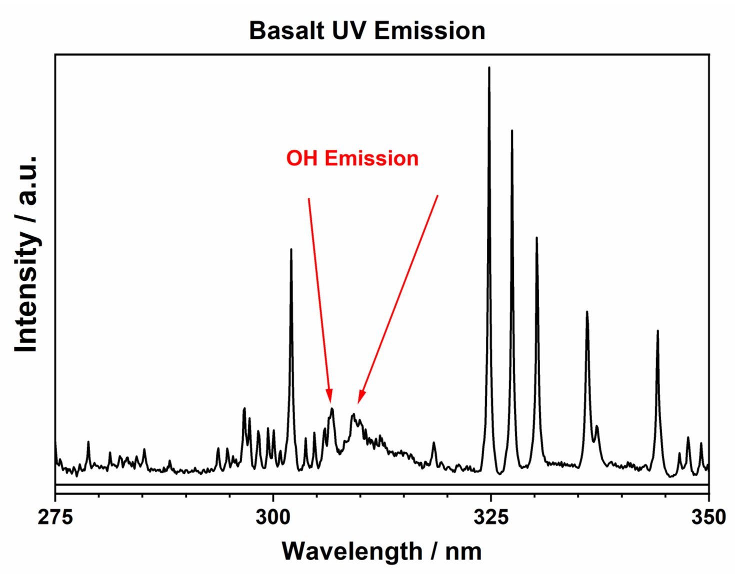
X-ray fluorescence data were collected on the melt layer of post-test specimen. Data collected on samples of basalt (fig. D, A & B) indicate that small quantities of volatiles are lost, and the concentrations of primary compounds remain invariant with respect to test condition. In contrast, Tamdakht (fig. D, C & D) loses significant quantities of iron and higher concentrations of volatiles under test conditions of increasing severity.

Melt viscosities (fig. E) were estimated using XRF data as input into a melt model developed by Giordano. The resulting data indicate the melt viscosity of basalt to be orders of magnitude higher than Tamdakht. However, basalt exhibits a more fragile melt than Tamdakht under the same test conditions (see images from high-speed video).

E. Melt Viscosity Estimate

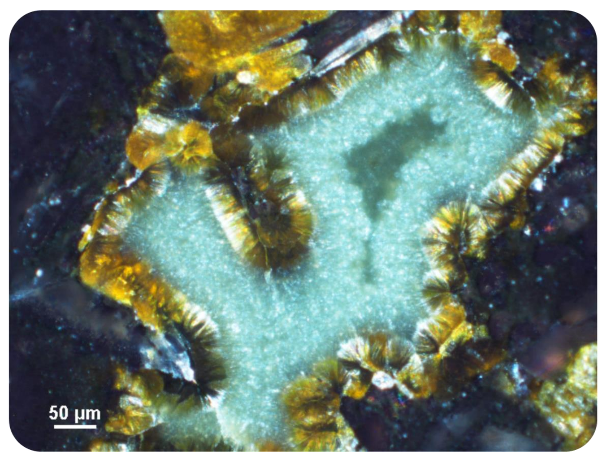


F. UV Emission Spectroscopy



Further insights can be gleaned from emission data collected in the post-shock region of each material. OH emission ($A_2\Sigma^+$- $X^2\Pi$) was detected in the post-shock region of basalt and absent during Tamdakht testing (fig. F). Furthermore, thin-section analysis of our basalt samples indicate the presence of secondary minerals (fig. G, blue green area). Therefore, the presence of OH is attributed to the rapid dissolution of secondary minerals (e.g., celadonite) that form in the vesicles of continental flood basalts.[4]

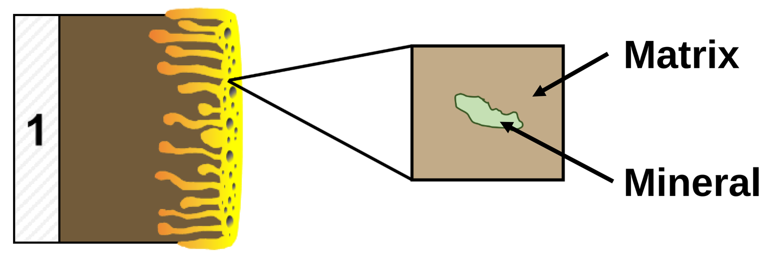
G. Basalt Thin-Section



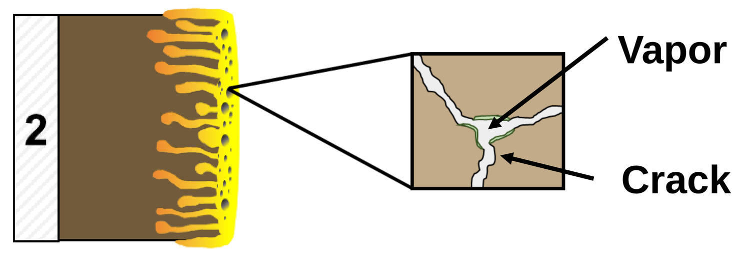
Zakharova et al. determined the average concentration of water in samples collected from the CRB group to be 1.4 ± 0.6 wt. %.[5] Furthermore, Cabato et al. analyzed the water content in olivine-hosted melt inclusions from basaltic lavas of the CRB group and results indicated concentrations as high as 4.0 wt. %.[6]

Water is a network modifier and is expected to destabilize the polymeric structure of siliceous melts. Thus, the melt viscosities of basalt were re-evaluated using XRF data and relevant concentrations of water as input. The results (fig. E, orange dashed lines) indicate that low concentrations of water decrease the melt viscosity of basalt by several orders of magnitude.

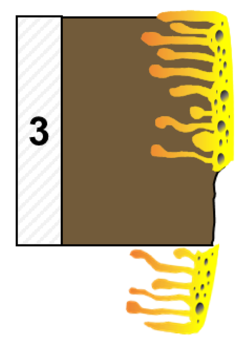
V. BASALT ABLATION MECHANISM



Step 1) Samples belonging to the CRB group contain hydrated minerals.



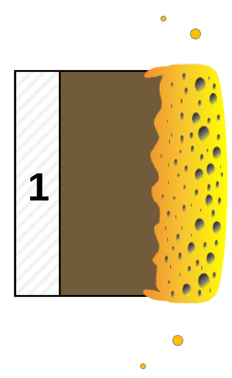
Step 2) Hydrated mineral decompose, and water vapor fills adjacent cracks.



Step 3) Expanding water vapor leads to mechanical fracturing of the subsurface material and periodic ejection of large sections of the viscous melt layer.

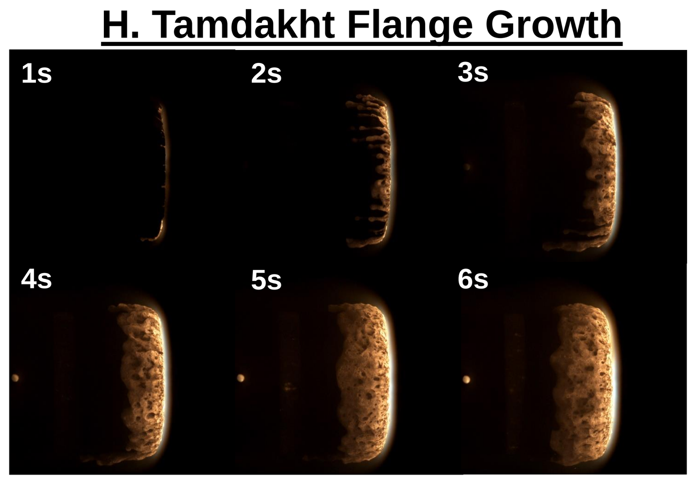
Finally, the viscosity of the hydrous melt layer is lowered by several orders of magnitude thereby enhancing the drag-induced flow and eventual spray into the hypersonic flow.

VI. TAMDAKHT ABLATION MECHANISM



- Mass loss is primarily attributed to the vaporization of volatile species (e.g., iron, sulfur, sodium, and potassium) which provide a protective layer.
- The loss of volatile species from an anhydrous melt results in higher viscosities and reduced spray.
- Thus, Tamdakht exhibits a relatively stable melt layer as evidenced by the build up of a siliceous flange at the edge of the sample (fig. H).

H. Tamdakht Flange Growth



VII. CONCLUSIONS

The ablation modes of Tamdakht and basalt were investigated in a high-enthalpy hypersonic flow environment. The results highlight the influence of water on the ablation mechanisms of hydrated meteor material. Carbonaceous chondrites contain relatively high concentrations of water (~ 10 wt. %). Therefore, future test campaigns will focus on the ablation mechanisms of carbonaceous chondrite simulants with varying concentrations of hydrated minerals.

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ACKNOWLEDGMENTS

This work was supported by the Asteroid Threat Assessment Project (ATAP) under the Planetary Defense Coordination Office (PDCO).

The authors would like to thank Scott Splinter and Jeff Gragg for their assistance in planning and executing the test campaign. Additionally, the authors thank Harlen D. Capen for capturing high-speed video and Bradly Butler for his expertise during the set up and collection of optical emission spectroscopy data.

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