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BALLISTIC PERFORMANCE MODEL OF CRATER FORMATION IN MONOLITHIC, POROUS THERMAL PROTECTION SYSTEMS

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ABSTRACT

Porous monolithic ablative systems insulate atmospheric reentry vehicles from reentry plasmas generated by atmospheric braking from orbital and exo-orbital velocities. Due to the necessity that these materials create a temperature gradient up to several thousand Kelvin over their thickness, it is important that these materials are near their pristine state prior to reentry. These materials may also be on exposed surfaces to space environment threats like orbital debris and meteoroids leaving a probability that these exposed surfaces will be below their prescribed values.

Owing to the typical small size of impact craters in these materials, the local flow fields over these craters and the ablative process afford some margin in thermal protection designs for these locally reduced performance values. In this work, tests to develop ballistic performance models for thermal protection materials typical of those being used on Orion are discussed. A density profile as a function of depth of a typical monolithic ablator and substructure system is shown in Figure 1a. From right to left, the figure shows the low density ablative material on the right and the substrate on the extreme left. The low density ablative generates a shock wave in the incoming threat, which if sufficiently high, facilitates the fragmentation/melt of the threat. The magnitude of the stresses from an impact are dependent on the impact velocity, u_i, and as the material decompresses as it propagates through the porous ablative at a particle velocity, u,

resulting in scattered fragments and a diffusion of molten material as shown in Figure 1b. The expansion ratio, ω, is the measure of diffusion of the fragmented/melted projectile and ablative material and is determined from the cavity radius, r, and depth, x. Due to the expansion of the material, the impact remnants are stopped over a reduced depth with a significant transfer of kinetic energy to thermal energy in the porous ablative due to pore collapse. These processes make the initial sound speed negligible in comparison to particle velocities, thus, the shock wave velocity, U, is approximately proportional to the particle velocity.

a) b)

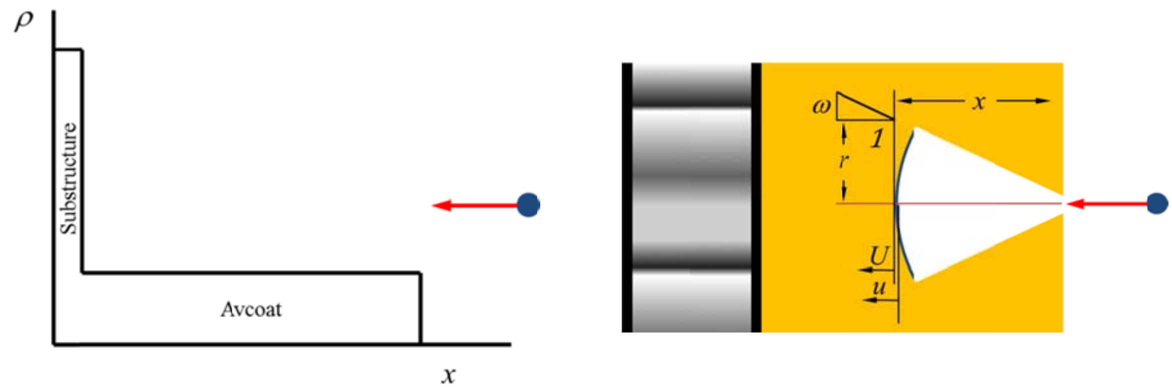

Figure 1 –Density Profile Experienced by a Projectile and Dispersion of Impact Debris in a Porous Monolithic

The acceptability of a locally reduced thermal protection system is limited with the key limit being a direct impingement of the reentry plasma on spacecraft structure. For regions of the vehicle that are subjected to the most intense reentry environments, this limit of acceptability can also be realized even if the structure is not directly exposed. For these cases the plasma within the cavity ingests enough energy from the flow field exterior to the bottom of the cavity to create a strong temperature gradient that heats structural elements above their safe operating condition despite the presence of residual thermal-protection material. The remaining thickness of insulating material after an impact is then an important parameter describing the worthiness of the vehicle to reenter. As such, the depth of penetration is the principal observable required when testing the performance of these materials to the orbital debris and meteoroid environments. In the testing reported here, these materials have been impacted with projectiles typical of the orbital debris environment and surrogate to the meteoroid environment to determine the depth of penetration.

Tests reported herein have been performed at NASA White Sands Test Facility's two-stage gas guns to $\gtrsim$ 8 km/s and at University of Dayton Research Institute's three-stage gas gun to ~ 10 km/s. Both facilities are capable of precision measurements of pre-test projectiles, impact velocities to ±0.2 km/s and projectile integrity verification prior to impact. Using the data obtained from hypervelocity impact tests of the monolithic Avcoat, a model using the material equation of state and strength properties of the monolithic thermal protection material has been developed that explains these findings and facilitates extrapolation to alternative materials configurations and impact conditions. The model addresses the initial interaction and deceleration of the projectile with the low density material and the resultant expansion and arrest of the impact debris. Solving the transcendental equation for critical mass to a given penetration depth can then be used to define the ballistic performance limit of a monolithic thermal protection material. The model has been shown to yield the penetration depths to within a few percent of over thirty impact tests using various sizes of Nylon, aluminum and steel projectiles with impact speeds between 3 to 10 km/s and obliquities from 0° to 75° to surface normal impacts.