Ballistic Performance of Porous-Ceramic, Thermal-Protection-Systems to 9 km/s

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Porous-ceramic, thermal-protection-systems are used heavily in current reentry vehicles like the Orbiter (1), and they are currently being proposed for the next generation of manned spacecraft, Orion (2). These materials insulate the structural components and sensitive electronic components of a spacecraft against the intense thermal environments of atmospheric reentry. Furthermore, these materials are also highly exposed to space environmental hazards like meteoroid and orbital debris impacts. This paper discusses recent impact testing up to 9 km/s on ceramic tiles similar to those used on the Orbiter. These tiles have a porous-batting of nominally 8 lb/ft^3 alumina-fiber-enhanced-thermal-barrier (AETB8) insulating material coated with a damage-resistant, toughened-unipiece-fibrous-insulation (TUFI) layer.

As the key function of these tiles is to insulate the reentry vehicle from reentry plasma, the remaining thickness of insulating material after an impact is 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 meteoroid and orbital debris environment. In the testing reported here, these materials have been shot with projectiles typical of the orbital debris environment (3) to determine the depth of penetration. In Figure 1, typical cavity records are shown for these tests. The upper X-ray image in Figure 1 shows a ceramic tile impacted by a 2.4 mm, 2017-T4 aluminum projectile at 7 km/s. In this image the cavity is enhanced in the X-ray by the inclusion of titanium powder. The lower X-ray image is similar where the ceramic tile damage cavity is created by a 1.6 mm, 2017-T4 aluminum projectile at 9.13 km/s. Also shown in the image are crater damage measurements of penetration depth and maximum crater diameter. As can be seen in the upper image, the damage measurements for the 7 km/s impact indicate that the crater depth is approximately 50% more than the maximum crater diameter with similar observations having been made for lower impacting kinetic energies at a similar velocity. The damage measurements of the 9 km/s cavity record show a similar observation. The most persistent fragments, visible as the thin traces, also show a depth of penetration that exceeds the diameter by about 50%. The notable difference between the 7 km/s record and the 9 km/s record is that at 9 km/s the depth of the bulk of the cavity is approximately equal to the cavity diameter. As plasma ingestion is proportional to the open area of the cavity, the persistent fragment traces are of negligible importance to the bulk of the cavity implying that the important characteristics of the tile response transition near 9 km/s.

To quantify the impact of this transition, a series of impact tests at velocities ranging from 7 to 9 km/s have been performed under normal impact conditions with aluminum projectiles, and the results are summarized in Figure 2. In this log-log figure the projectile mass is shown versus the through-thickness areal density of the ceramic tile penetrated normalized to the units of grams and grams per square centimeter, respectively. In this figure, the test results are sorted into impact speed bins of 7 km/s, 8 km/s and 9 km/s impacts represented by blue, green and red points, respectively. As can be seen from this figure that in this plane the dependence for impacts at 7 km/s is linear; consequently, there is a power-law dependence for the projectile mass on arresting areal density. It can also be seen that the areal density required to arrest particles at higher velocity is less than that required at 7 km/s for a similar projectile. This behavior is further illustrated in Figure 3 where the ratio of the arresting areal density of the tests in Figure 2 is normalized to the power-law model at 7 km/s for the projectile used in the test. In this figure, the required arresting areal density ratio is shown as a function of velocity. Points above one on the ordinate indicate that more areal density is required to arrest the particle than that required at 7 km/s. Points below one indicate that less areal density is required to arrest the particle; put differently, the tile can tolerate larger projectiles at a given relative velocity. As can be seen in the figure, at just over 8 km/s tiles begin arresting projectiles with less through-thickness material removed.

These observations indicate a transition in the penetration mechanism that occurs for aluminum at high velocities. The implication of these observations is that a projectile under higher velocity impacts (≥8 km/s) penetrate less resulting in larger particles being tolerated before the reentry damage threshold is achieved. In this paper these tests results and others are discussed within the framework of a model that uses a constant ratio of specific heats for the plasma that is created in the porous, insulating-material of the tile during an impact (4). This simplification of the material equation-of-state is used to develop an analytic self-similar solution to the hydrodynamic equations. This model along with hydrodynamic simulations are used to demonstrate material equation-of-state influences that account for the high velocity (≥8 km/s) behavior and to provide an empirical framework for further extrapolating these test results. These empirical extrapolations are compared with heritage models (5) for these materials developed from testing at lower velocities. An assessment of predicted spacecraft risk based upon these results is also discussed.

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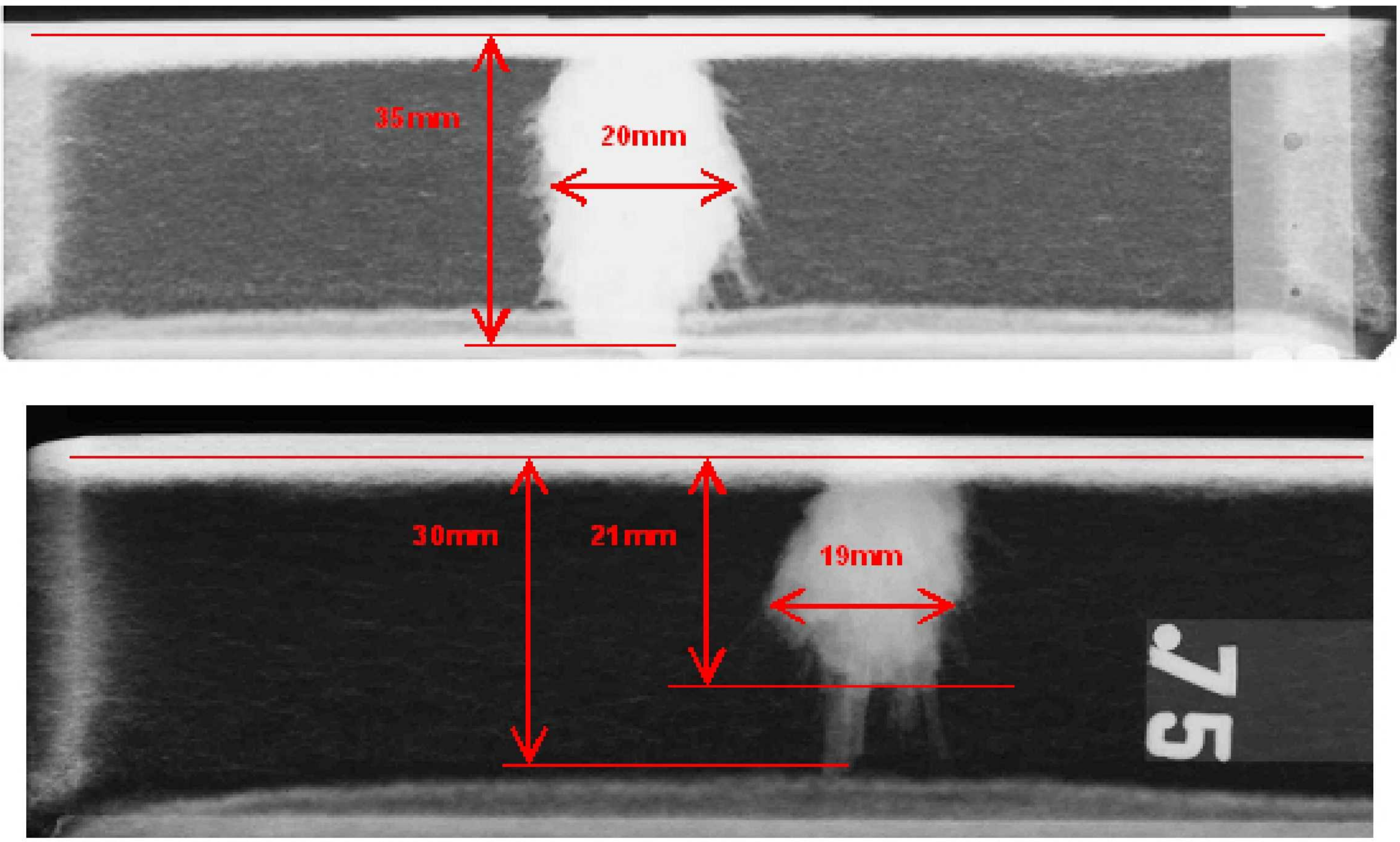

Figure 1-Test performance of AETB-8 tiles to 9 km/s impact

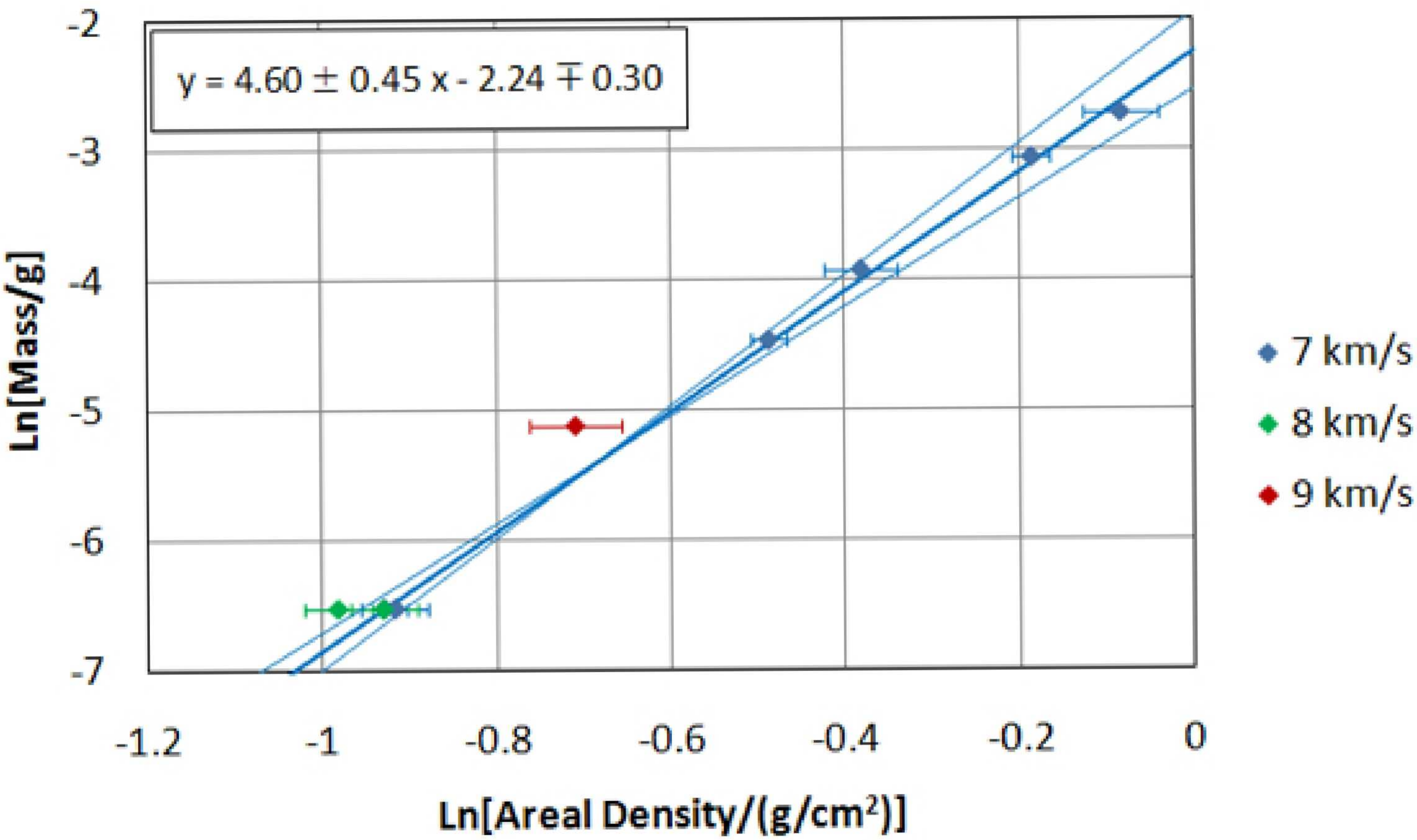
y = 4.60 ± 0.45 x - 2.24 ∓ 0.30
-2
-3
-4
-5
-6
-7
Ln[Mass/g]
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
Ln[Areal Density/(g/cm²)]
7 km/s
8 km/s
9 km/s

Figure 2

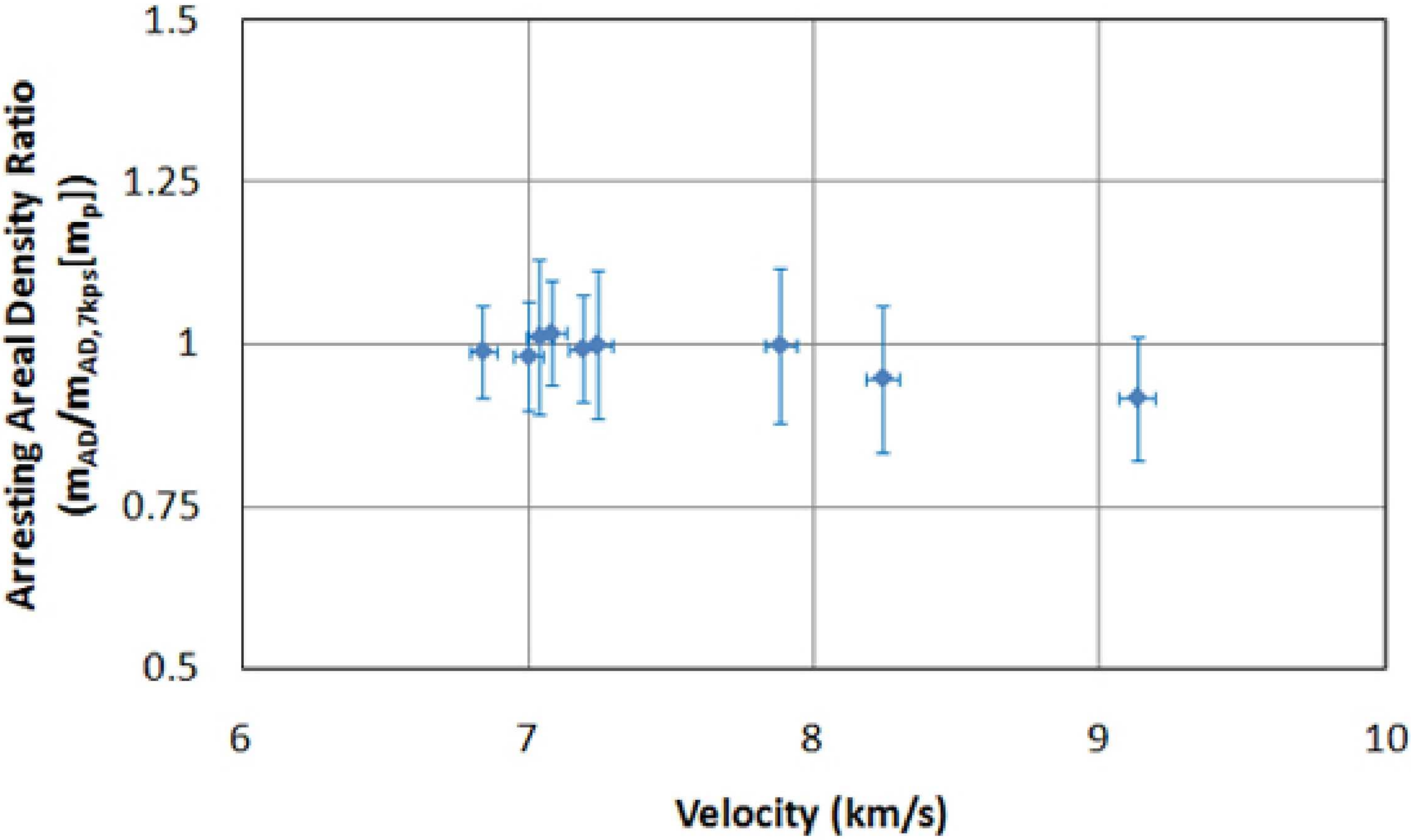
Arresting Areal Density Ratio
($m_{AD}/m_{AD,7kps}[m_p]$)
1.5
1.25
1
0.75
0.5
6
7
8
9
10
Velocity (km/s)

Figure 3