Orion Spacecraft MMOD Protection Design and Assessment

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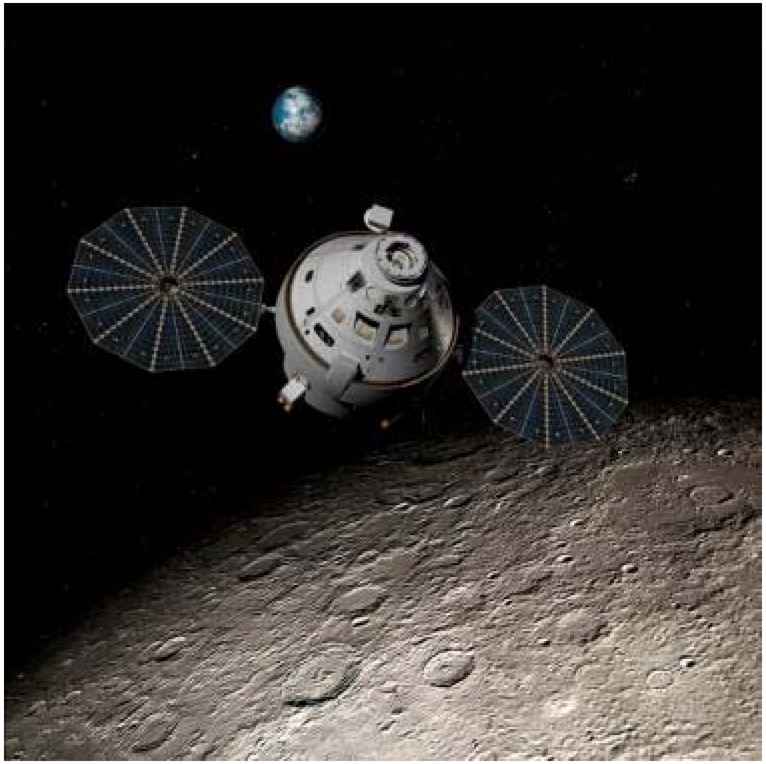
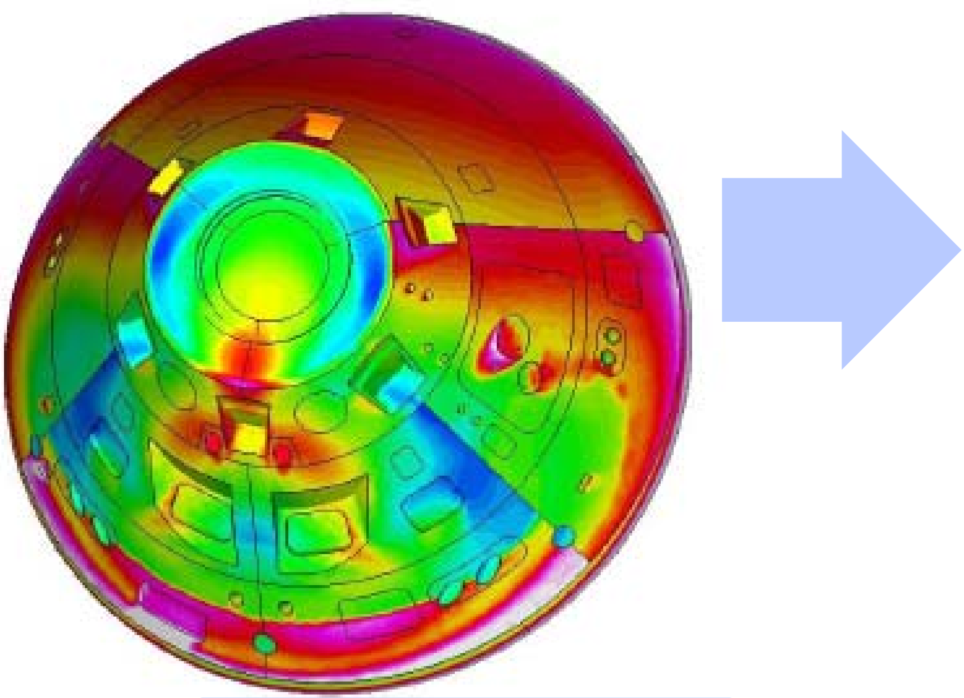
A first-principals, semi-empirical ballistic performance model has been developed for porous ceramics

- Lightweight thermal protection systems protect the crew and vehicle of orbital and exo-orbital missions from the intense heat of atmospheric reentry
- To maintain low launch weights these materials are their own protection from space hazards like orbital debris and meteoroids
- A ballistic performance model is described here that models the performance under a variety of impact conditions



Atmospheric braking creates high surface temperatures that must be mitigated



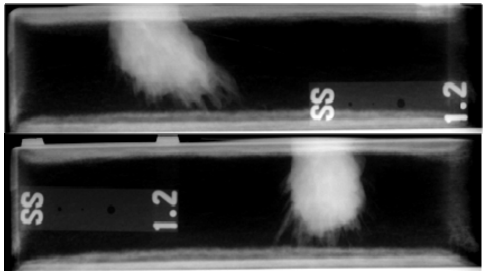
- The Orion thermal protection system surfaces can be heated by the reentry plasma to temperatures above 1000 °K creating thermal gradients of several 100 °K over their thickness

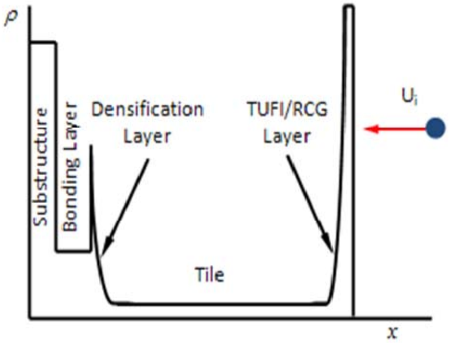
- The small dimensions of high probability impacts afford some damage tolerance due to limited thermal convection in the small cavities leaving the residual insulation as the key performance parameter

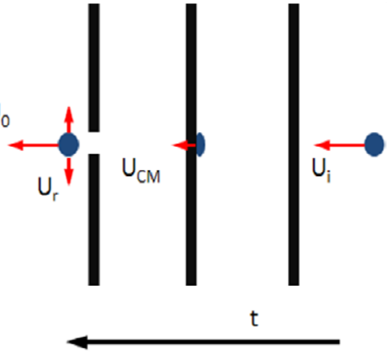
Tests of Orion thermal protection tiles are used to establish the thresholds of failure

- AETB8 impacts have performed by Orion program at:
  - UDRI with maximum velocities of ~10 km/s
  - WSTF with maximum velocities of ~8.5 km/s
- 50 internal tile damage impacts have been performed
  - Impactors include Nylon, Aluminum and Steel
  - Impact obliquities from normal to 75° to normal
  - Impact velocities from 3 to 10 km/s
  - 2 different areal densities of hard outer layer

Impacts on tiles involves a sequence of densities that distribute impact energy





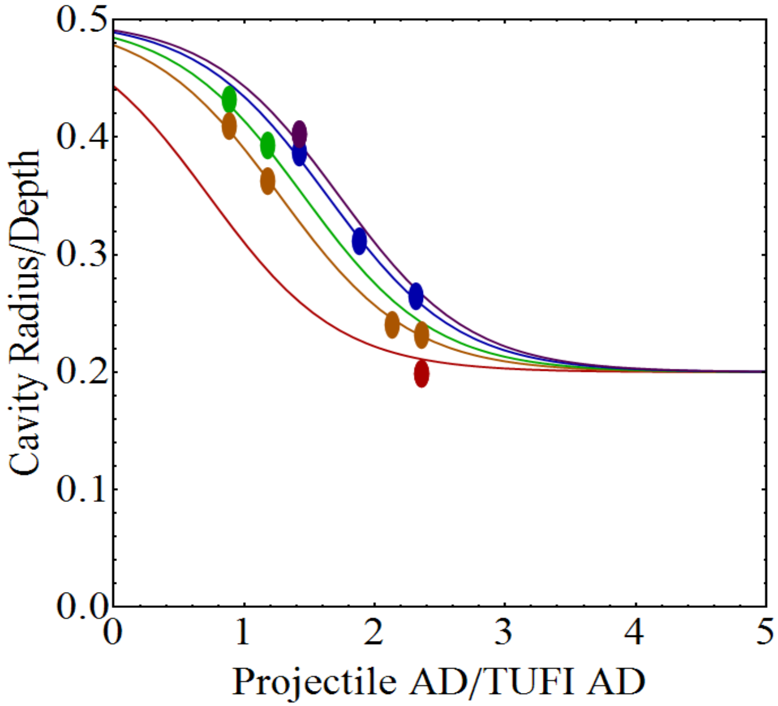


- Projectile impacts the higher density TUFI/RCG layer and creates a cavity as it goes through the lower density tile

- The density profile:
  - High density TUFI/RCG layer
  - Low density tile
  - Higher density silica layer and bonding layer

- Projectile slows to equilibrium in the TUFI/RCG layer and then releases to an initial velocity, U_0, and a lateral release velocity, U_r, in the tile

A modified logistics function reproduces the ratio of cavity depth to half-width

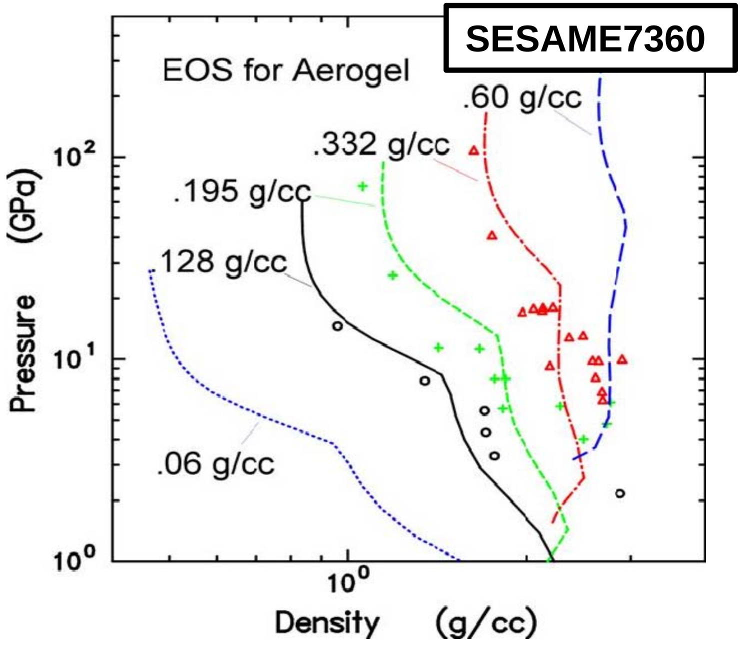


- Points are shot data color coded to the corresponding velocity bin (km/s): 4 (red), 7 (orange), 8 (green), 9 (blue), 9.5 (magenta)

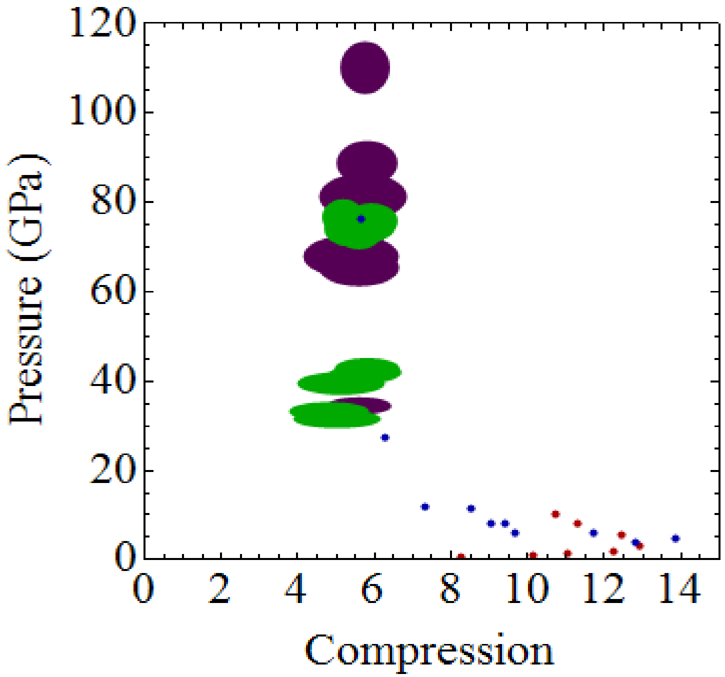
$$\omega = \frac{\delta\omega}{Exp\left[\frac{\overline{m_p}\,U_m - \overline{m_T}\,U_i}{1/2\ \overline{m_T}\,U_m}\right] + 1} + \omega_0$$

- Empirical relation
- Fit parameters:
  - $\delta\omega$ is 0.3
  - ω_0 is 0.2
  - U_m is 5.5 km/s
- Represents fraction of dispersed projectile and TUFI to large fragments
  - First term numerator is the product of required pressure and time in projectile for break up
  - Second term numerator is the product of induced pressure of the impact and time to rarefaction generation
  - Denominator is the dispersion of pressure and time about the required

EOS studies show approximately isochoric behavior in jump states of porous silica

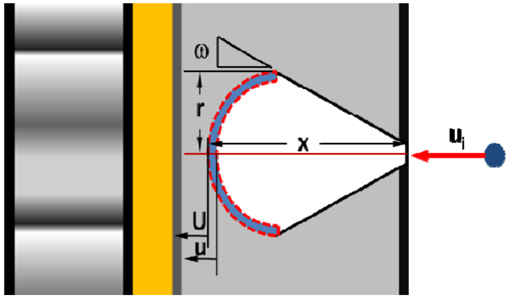


- N. C. Holmes and E. F. See in Shock Waves of Condensed Matter of 1991 with a SESAME 7360 P-α compaction of 2.5 GPa for P_s overlaid



- T. R. Boehly, *et al.* in Shock Waves of Condensed Matter of 2007 extended silica observations for 0.2 g/cc aerogels to much higher pressures indicating continual significant energy sinks

Mass, EOS and momentum equations combine to a 1st order differential



$$\frac{d\,Mu}{dt} = \frac{M}{s_0}\,\frac{d\,U^2/2}{dx} = -F_H - F_M$$

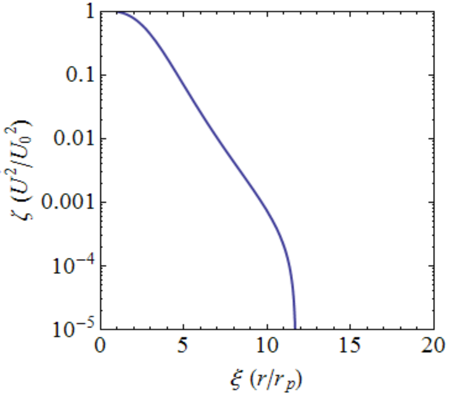
$$F_H = \rho_0\left(\frac{U^2}{s} + \frac{\rho}{\rho_0}\left(\frac{U}{s} - U\right)^2\right)A$$

$$F_M = Y_0\,A$$

$$M = \left(\frac{4\,\rho_p\,r_p}{3} - \frac{\rho_0\,r_p/\omega}{3}\right)\pi\,{r_p}^2 + \frac{\rho_0\,A\,x}{3}$$

$$\frac{1}{s_0}\left(\frac{\mu - 1/3}{\xi^2} + \frac{\xi - 1}{3}\right)\frac{d\,\zeta}{d\xi} + \frac{s_0 + 1}{s_0}\,\zeta = -\psi$$

$$U_0 = s_0\,U_i\left(\frac{\overline{m_p}}{\overline{m_p} + \overline{m_T}}\right)^{\frac{1+s_T}{2}}$$

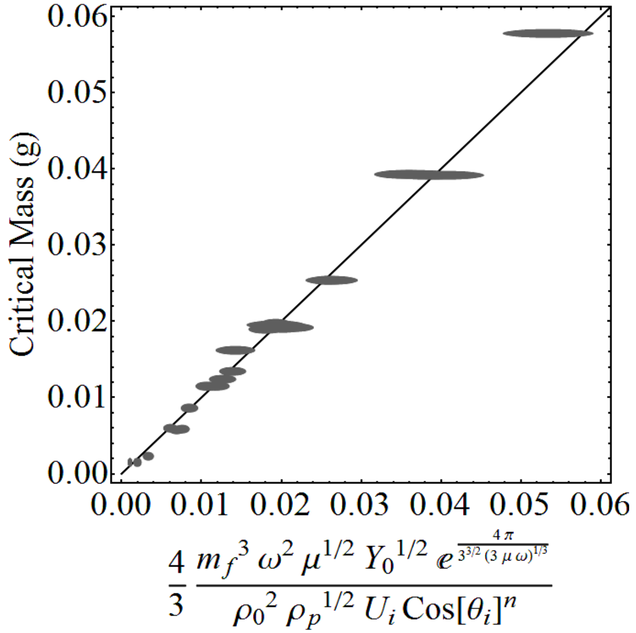


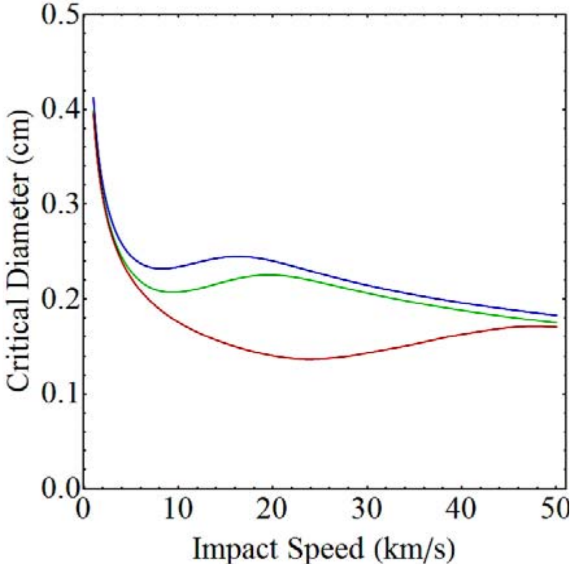
- The disrupted projectile expands as it traverses the tile scattering increasing mass to slow faster than a fully intact projectile does

- The non-dimensional Lagrangian form of the mass, EOS and momentum equations (see Appendix of accompanying paper for full derivation)

- The normalized equation for projectile velocity decreases rapidly under expansion until the strength of the tile finally arrests the projectile

Model reproduces the tests performed and shows evidence of a double wall behavior

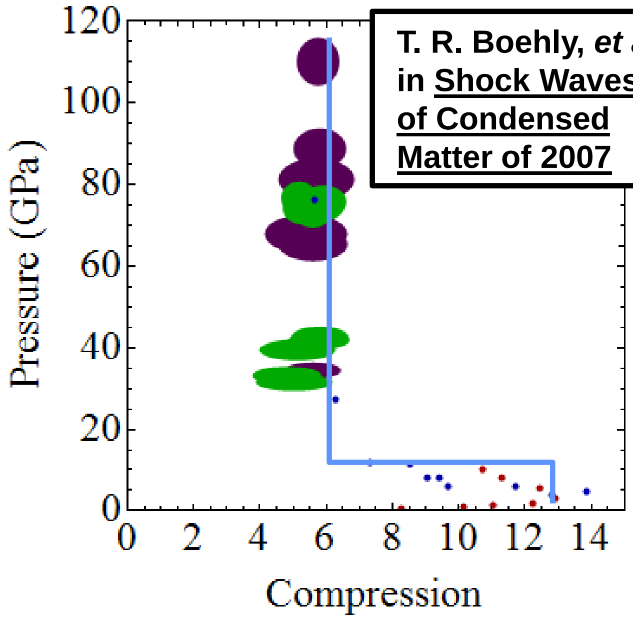




- Simplified solution of the model reproduces
  - Nylon, aluminum and steel projectiles
  - Impact obliquities to 75° to normal
  - Impact velocities to 10 km/s
  - Light and Heavy TUFI/RCG

- Model shows the double wall effect of fragmentation/melt of impactors
- Shows the dependence of the onset of fragmentation/melt of impactors on weight of TUFI/RCG layer

Higher impedance at high shock wave strengths may also increase performance



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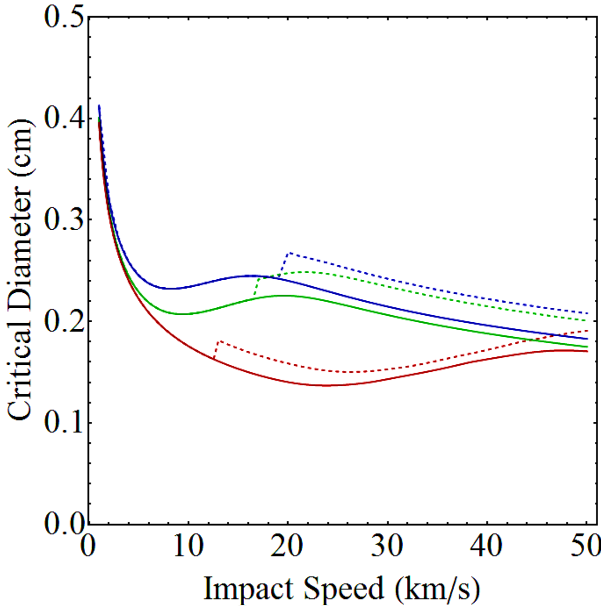
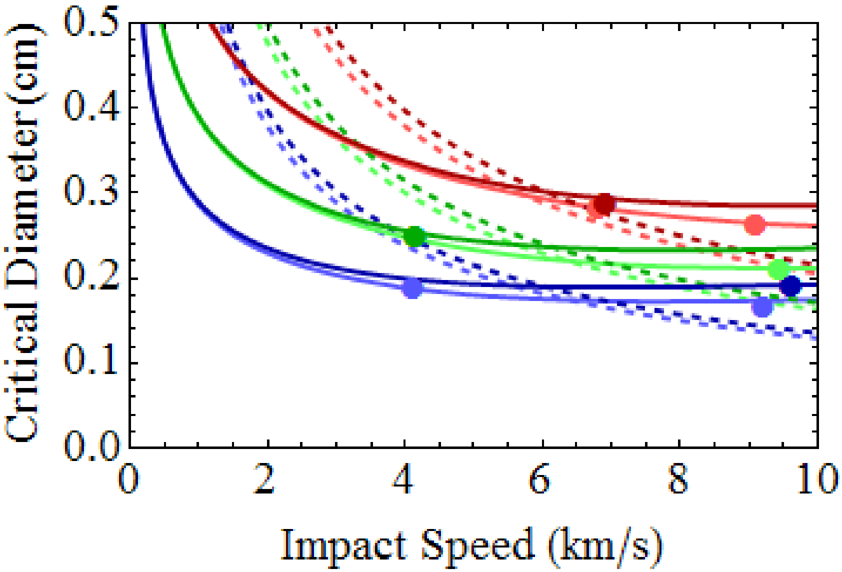


- Equation of state measurements show that below ~10 GPa a porous silicates compress to near solid density and experiences a ~6x compression above
- This behavior can be approximated with a piecewise shock wave slope

- Higher impedance could result in higher performance at higher impact speeds typical of meteoroids
- Onset is at lower impact velocities for lighter outer layers

The implemented ballistic limit equation lowers risk predictions considerably



- Predicted risk associated with this model relative to an energy scaled model is 60% lower for orbital debris and 95% lower for meteoroids at ISS orbital parameters

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- To maintain low launch weights these materials are their own protection from space hazards like orbital debris and meteoroids
- A ballistic performance model is described here that models the performance under a variety of impact conditions
- Using the model described here relative to an energy scaled model results in a significantly reduced prediction of full penetration of this material at ISS orbital parameters