Heatshield Erosion due to Dust Particle Impacts on the Schiaparelli Capsule During Martian Entry

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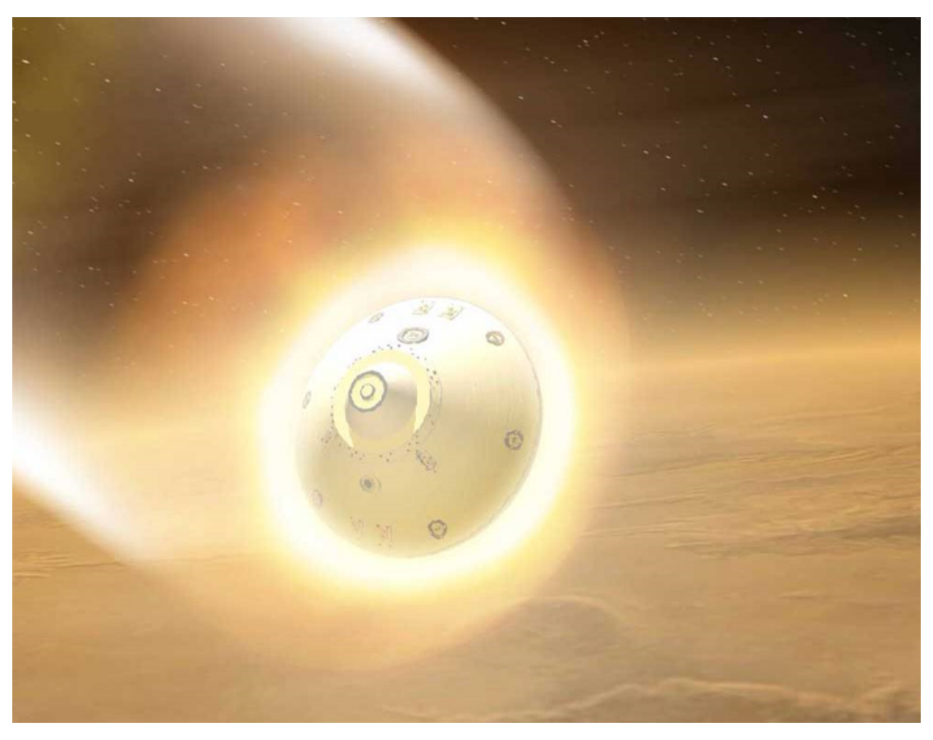
Abstract: One of the unique features of spacecraft entering the atmosphere of Mars is the possibility of a major dust storm occurring during the entry. Design of the thermal protection system (TPS) for Mars missions have to account for the possibility of dust erosion when estimating the thickness of the TPS. Because weight is always a critical factor in designing entry vehicles, accurate assessment of dust erosion is necessary to avoid over-design of the TPS.This study will present computational results of heatshield erosion due to dust particle impacts on the ExoMars Schiaparelli capsule if it had encountered a dust storm during its October 2016 entry. A one-way coupling approach is used where particle trajectories are computed based on an underlying CFD flow solution. Based on a distribution of particle sizes ranging from 1 to 18 microns in diameter, the Icarus material response solver predicted approximately 1 mm of TPS heatshield erosion due to particle impacts, which was 40% of the value due to material charring.

Motivations....

- A spacecraft entering the Martian may encounter a global or regional dust storm.
- Design of the TPS of a mars entry vehicle must include an estimate of the surface erosion caused by dust particle impacts.

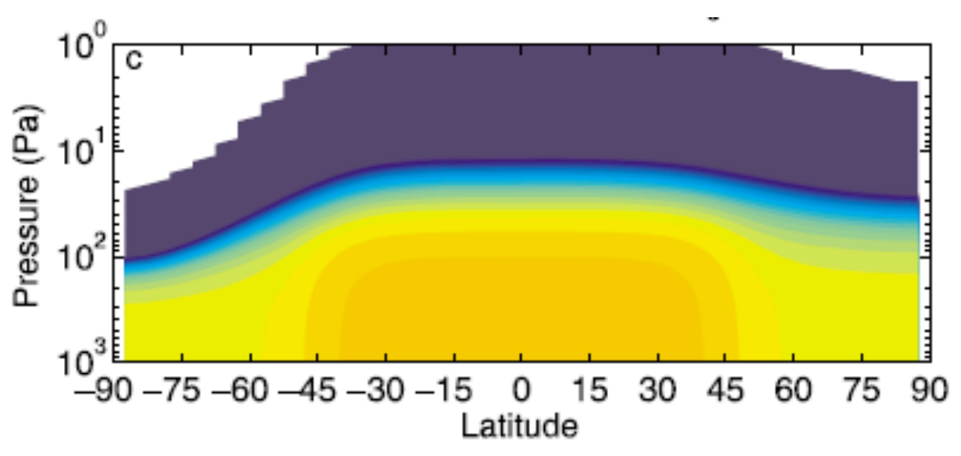


The Mars entry environment may include dust particles

The goal of the current work is to use a Lagrangian particle trajectory method along with the Icarus material response code to model the TPS surface erosion due to dust particle impacts for a Mars entry.

Martian Dust Storms

- Based on observations taken over decades, major global dust storms occur on the average of once every 3–4 Earth years [1], but the timing of them is unpredictable.
- During major global dust storms, dust particles can extend up to 50 km in altitude for 20-50 days after the start of the storm.



Density-scaled dust opacity for Mars Climate Database MY24 scenario. Figure from Ref. [2].

Dust Particle Size and Vertical Distribution

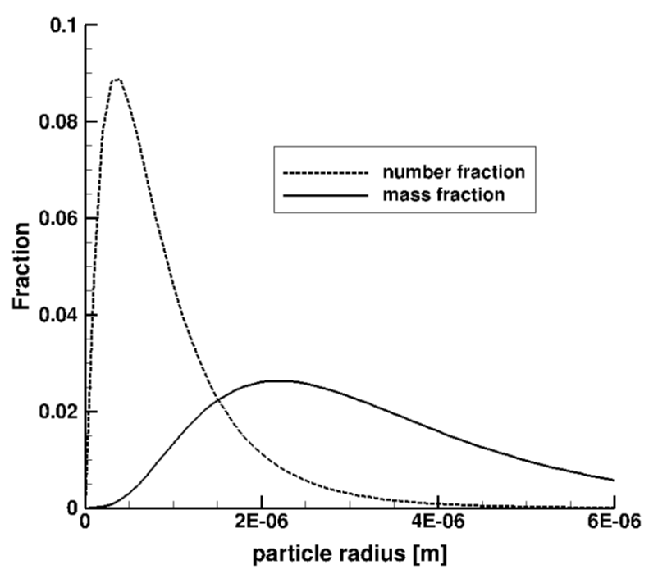
- A modified gamma distribution was used to model dust particle size distribution [2].

$$N(r) = c r_p^2 exp\left(-4\left({}^{r_p}/_{r_m}\right)^{0.5}\right)$$

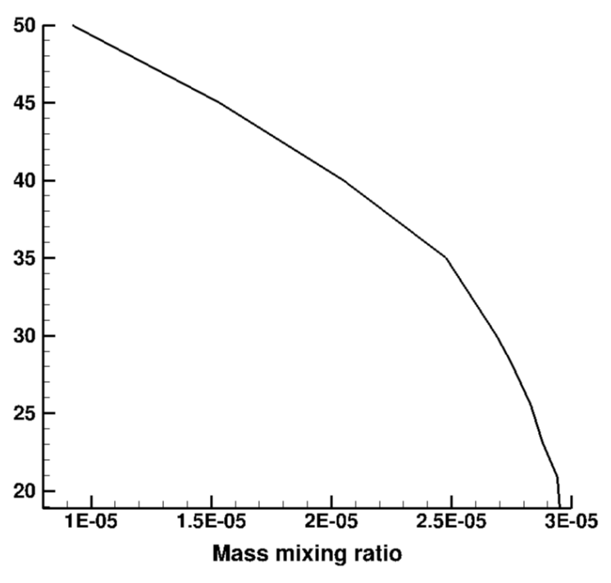
- Vertical distribution of mass mixing ratio determined using Conrath equation with density-scaled opacity of 1.1e-3 m2/kg at 20 km altitude - Consistent with data from Ref. [2].

$$q = q_0 exp\left[v\left(1 - {}^{p_0}/_{p}\right)\right]$$

- Most numerous particle radius is 0.4 micron. Particle radius with highest mass fraction is 2.2 micron.



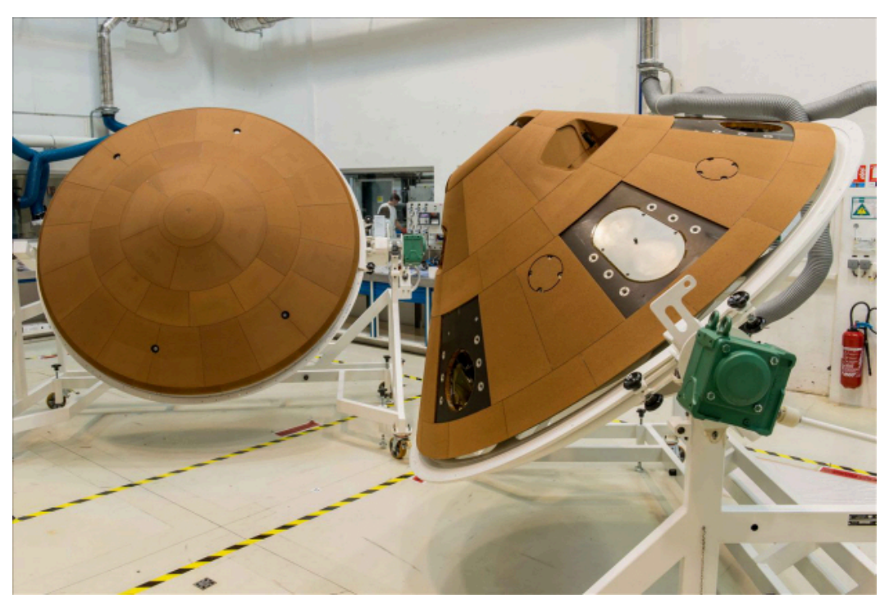
Dust particle size distribution.



Mass mixing ratio vs altitude

ExoMars Schiaparelli Capsule

- The ExoMars Schiaparelli Capsule was a 2.4 m diameter, 70-deg sphere cone. Entered the Martian atmosphere in October, 2016.
- One of the Schiaparelli mission goals was to enter the Martian atmosphere during a dust storms to perform atmospheric and surface measurements in the dust-rich environment. (Dust storm didn't happen)
- Schiaparelli provides a realistic test case for TPS dust erosion analysis.



ExoMars Schiaparelli Entry Capsule

Surface Damage Models

- Dust particle surface damage models developed by Papadopoulos, et al. [3] were based on Apollo- and Shuttle-era experimental data.
  - Experimental particles were 100x larger than Martian dust particles. Upcoming tests at DLR will use smaller particles.
- Crater diameter and penetration depth functions of particle diameter and velocity at impact.

$$\frac{D_c}{d_p} = 0.048{v_p}^{0.667} \qquad \frac{p}{d_p} = 0.024{v_p}^{0.667}$$

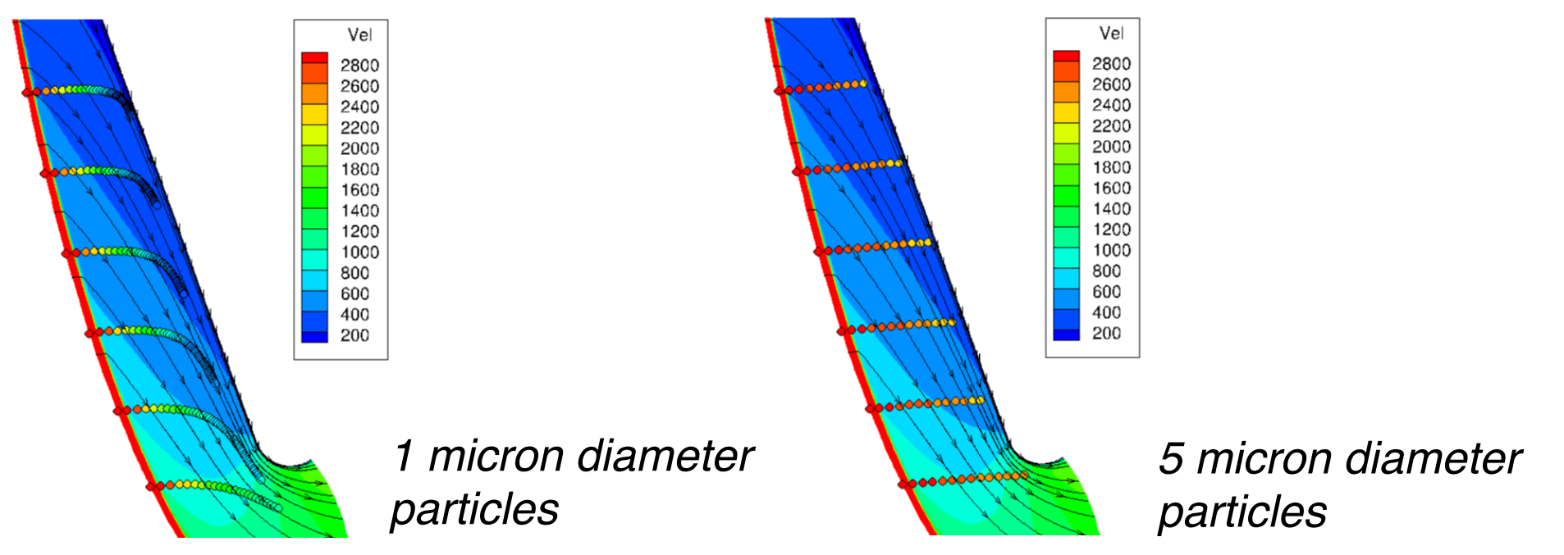
Surface damage relations for AVCOAT TPS from Ref. [3].

Particle Trajectory Calculations

- Particle trajectories computed using a Lagrangian method.
- One-way coupling: particles assumed to not influence shock layer flow.
- Particle location, velocity, temperature, and diameter computed by solving coupled set of ordinary differential equations (ODEs) using underlying DPLR code [4] CFD solutions at 9 trajectory points.

$$\frac{d\overrightarrow{V_p}}{dt} = \frac{3}{4}\frac{\rho}{\rho_p}\frac{C_D}{d_p}(\Delta V^2) \qquad \frac{dT_p}{dt} = \frac{6h}{\rho_p c_p d_p}\left(T - T_p\right) \qquad \frac{d(d_p)}{dt} = \frac{2h(T-T_v)}{\zeta\rho_p}$$

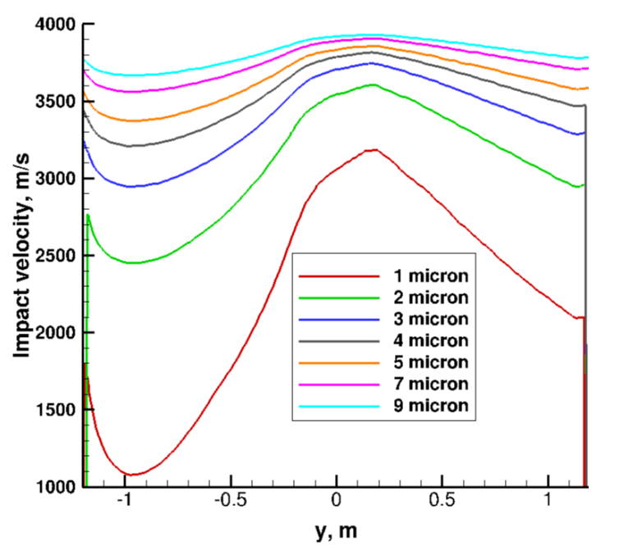
- Particles ranging from 1 to 18 microns in diameter started at 201 equispaced locations along outer boundary of CFD grid. Trajectories computed until particles strike the heatshield or travel around it.



1 micron diameter particles

5 micron diameter particles

Particle velocities overlaid on DPLR CFD shock layer flow solution, 30 km altitude

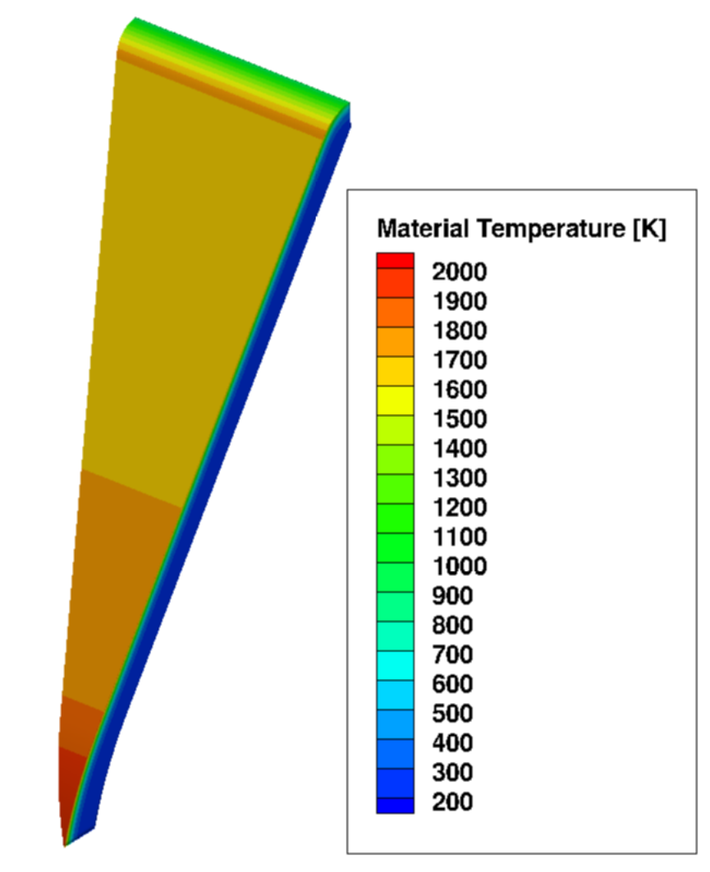


- Quantities needed for surface damage assessment extracted from particle trajectory solutions.
- Capsule was at small angle of attack ranging from 3-7 deg.

Particle impact velocities as a function of particle diameter, 35 km altitude

Icarus Material Response Code

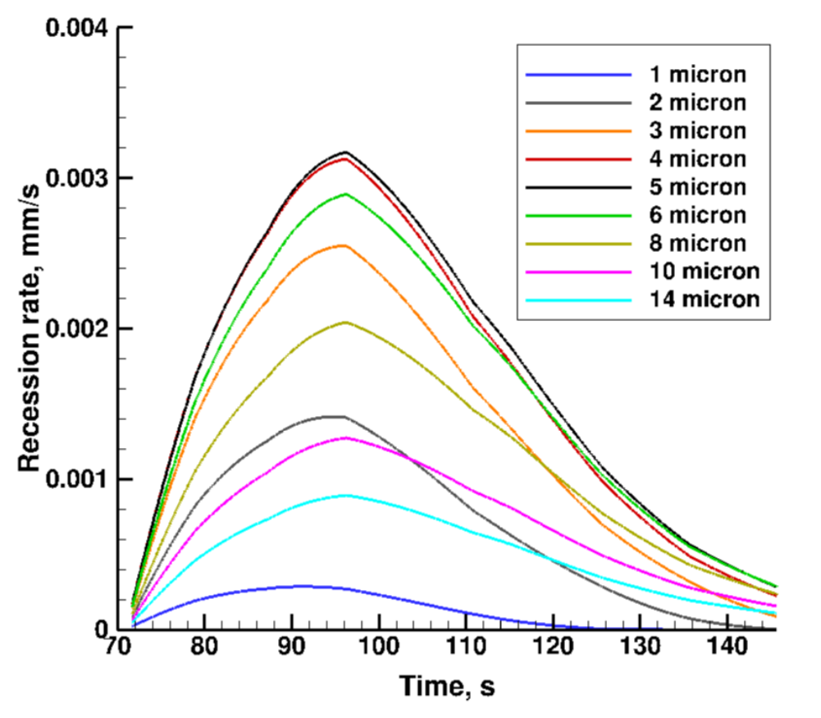
- Icarus is a 3-D, finite-volume, unstructured material response code [5].
- Erosion boundary condition implemented in Icarus as part of a general aeroheating surface energy balance.
- Time- and spatially-varying inputs including particle impact velocity, diameter, and number density provided to Icarus along entry trajectory.



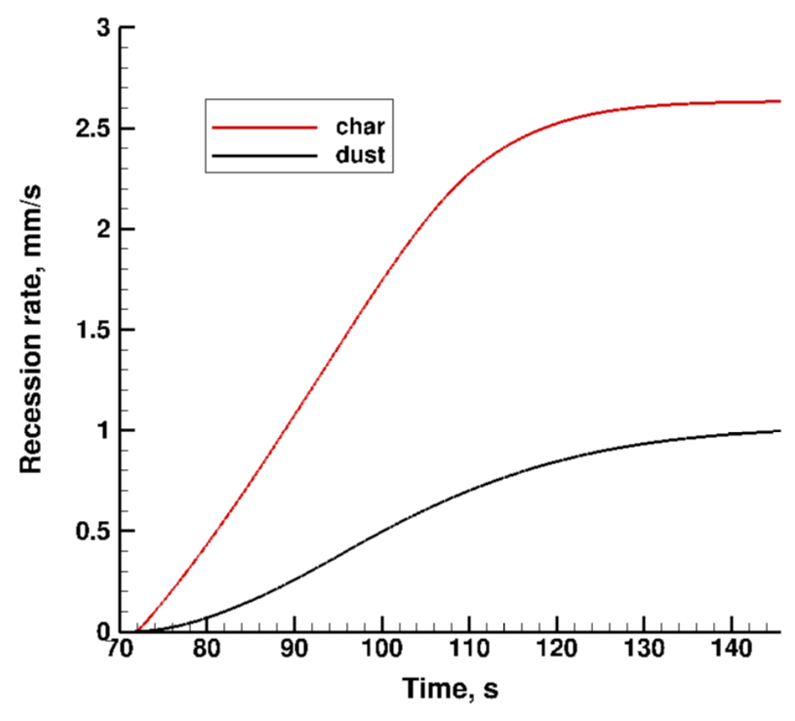
Temperature contours, Schiaparelli capsule, 50 km trajectory point.

Results

- Icarus run for 84 seconds of simulation time to compute TPS surface erosion due to dust particle impacts and charring between altitudes of 50 - 20 km.
- Schiaparelli heatshield material, Norcoat Liege tiles, not available in Icarus material database. PICA was used instead - no effect on dust erosion calculations.
- The surface damage model for AVCOAT was used.
- Peak dust erosion rate at the stagnation point occurs at 96 sec (35 km) trajectory point. 4- and 5-micron diameter particles cause the most damage.
- Total surface recession at the stagnation point due to dust particle impacts was about 1 mm, which was 40% of the erosion due to PICA charring.



Surface recession rates as function of particle diameter.



Cumulative stagnation point surface recession.

Summary/Conclusions

- TPS surface recession computed for the Schiaparelli entry capsule during its entry into Martian atmosphere.
- Lagrangian, one-way coupling technique used to compute particle trajectories through the shock layer at 9 trajectory points.
- Icarus material response code predicted total surface recession due to dust particle impacts of 1 mm at the stagnation point, about 40% of the recession due to charring.

Future Work

- Compare one-way coupling results with two-way discontinuous Galerkin code being developed by E. Ching and M. Ihme at Stanford.
- Develop updated dust erosion damage models using new experimental data from DLR.

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References:

[1] Zurak, R.W., "Martian Great Dust Storms: An Update," *Icarus*, Vol. 32, pp. 288-310, 1982.
[2] Heavens, N., Richardson, M., Kleinbohl, A., Kass, D., McCleese, D., Abdou, W., Benson, J., Schofield, J., Shirley, J., and Wolkenberg, P., “The vertical distribution of dust in the Martian atmosphere during northern spring and summer: Observations by the Mars Climate Sounder and analysis of zonal average vertical dust profiles,” *Journal of Geophysical Research*, Vol. 116, pp. 1-23, 2011.
[3] Papadopoulos, P. Tauber, M., and Chang, I-D., “Heat Shield Erosion in a Dusty Martian Atmosphere”, Journal of Spacecraft and Rockets, Vol. 30, No. 2, pp. 140-151, 1993
[4] Wright, M., White, T., and Mangini, N., "Data Parallel Line Relaxation (DPLR) Code User Manual Acadia - Version 4.01.1, 2009.
[5] Schulz, J., et al, "Development of an Unstructured, Three-Dimensional Material Response Code," AIAA Paper 2017-0384, Jan. 2017.