Tales from the Mars Science Laboratory Thermal Protection System Development (or, Try Not to Panic When Your Heatshield Material Disappears)

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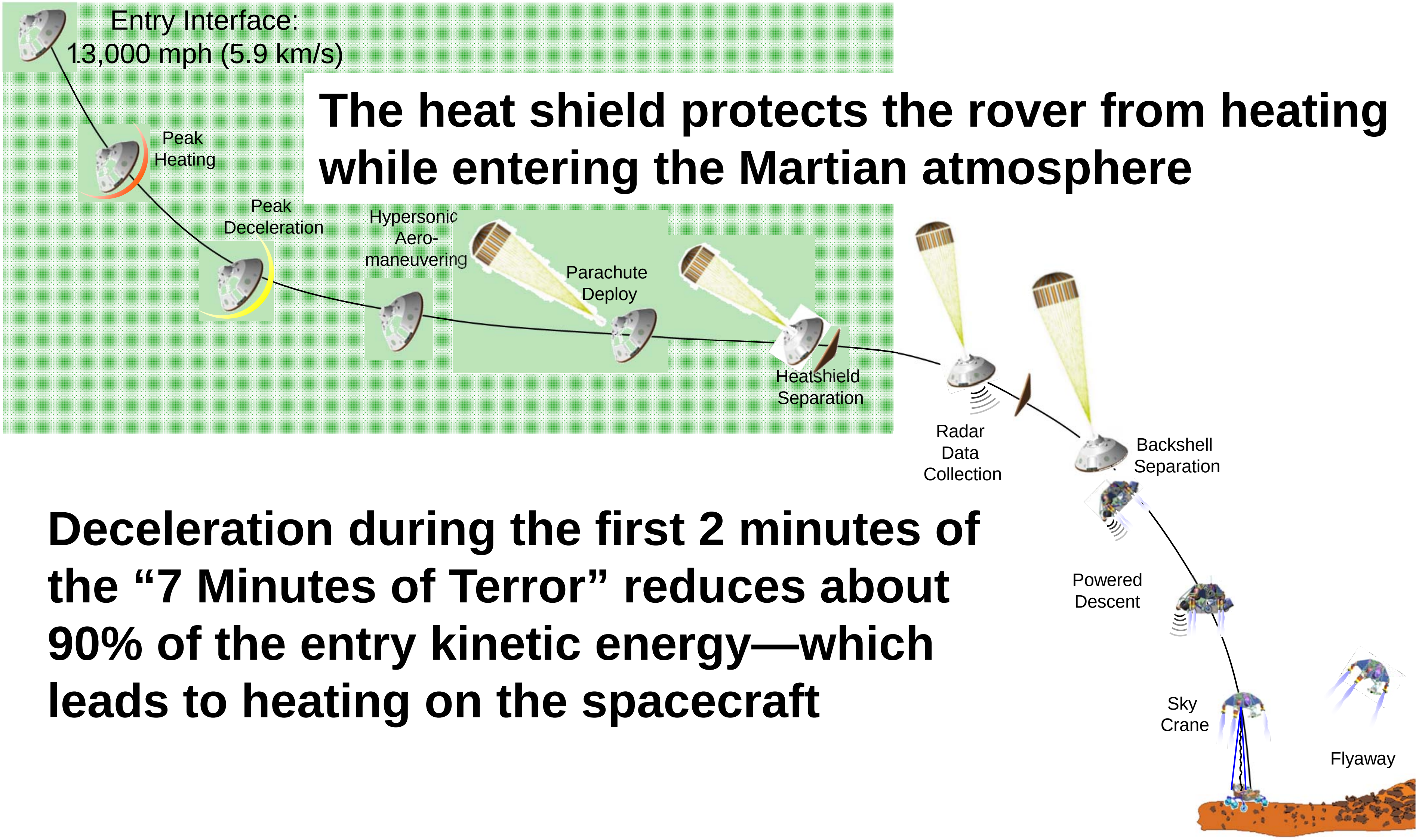
Who Am I?

- BSEE, MSEE, and PhD from University of Illinois at Urbana-Champaign
- Background in simulating plasma physics for semiconductor processing applications
- At NASA Ames for 20 years
- Project Manager for Mars Science Laboratory (MSL) Thermal Protection System (TPS), and same role for Mars 2020 mission
- Currently the Science Missions Development Manager for Entry Systems and Technology Division

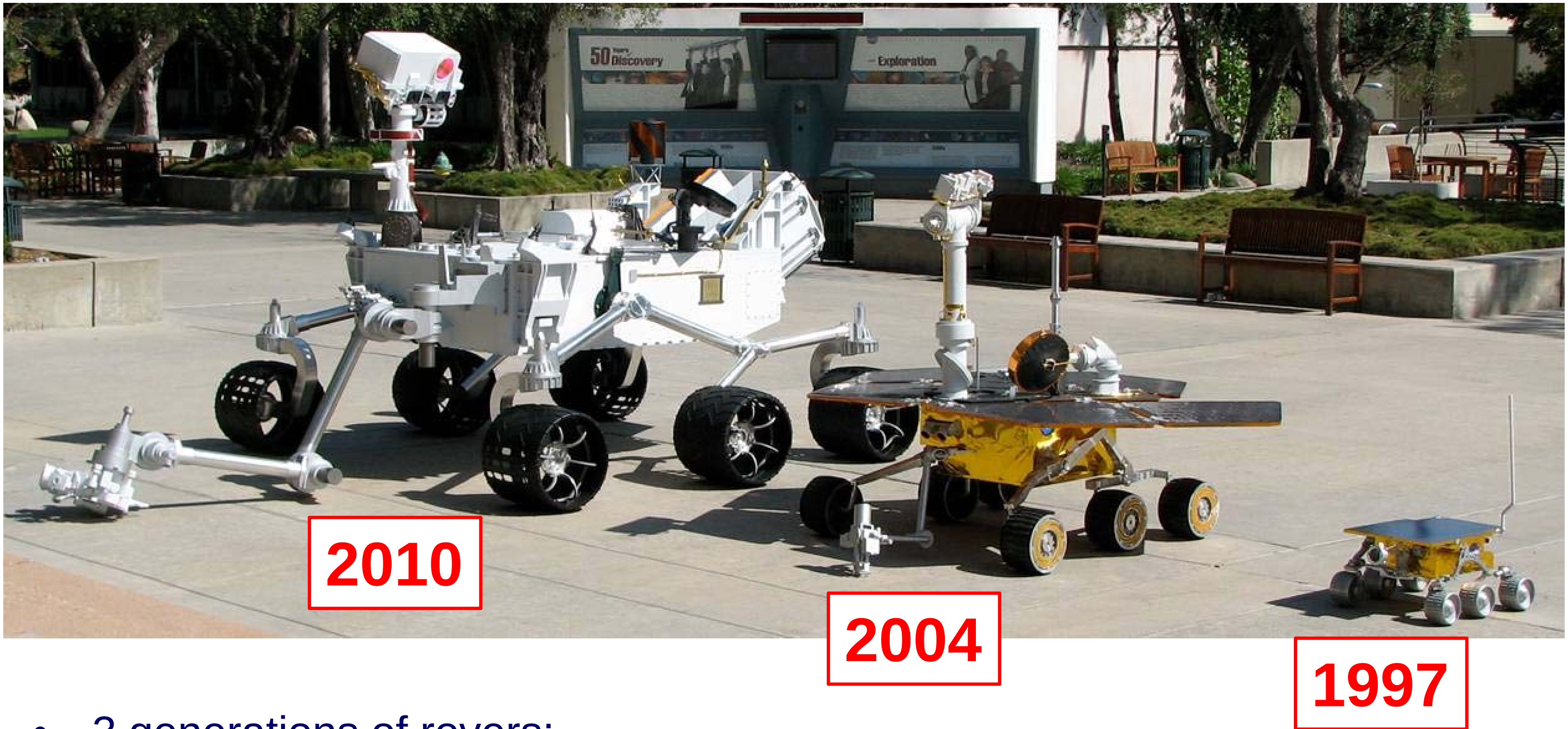
Entry, Descent, and Landing



The heat shield protects the rover from heating while entering the Martian atmosphere

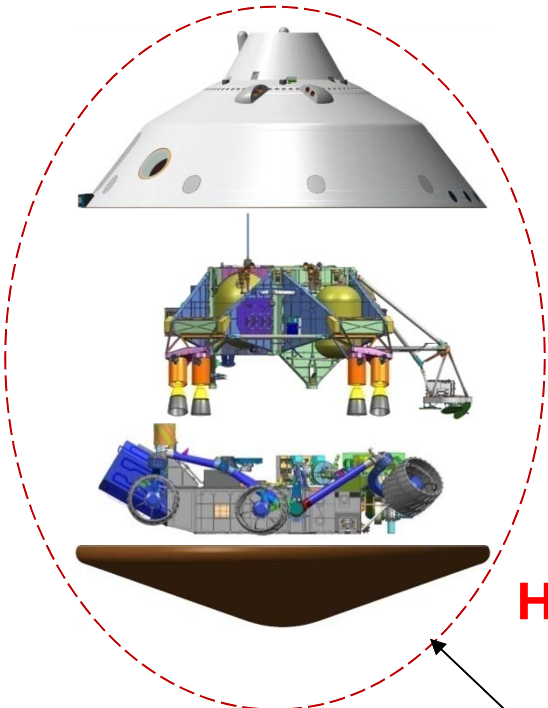
Deceleration during the first 2 minutes of the "7 Minutes of Terror" reduces about 90% of the entry kinetic energy—which leads to heating on the spacecraft

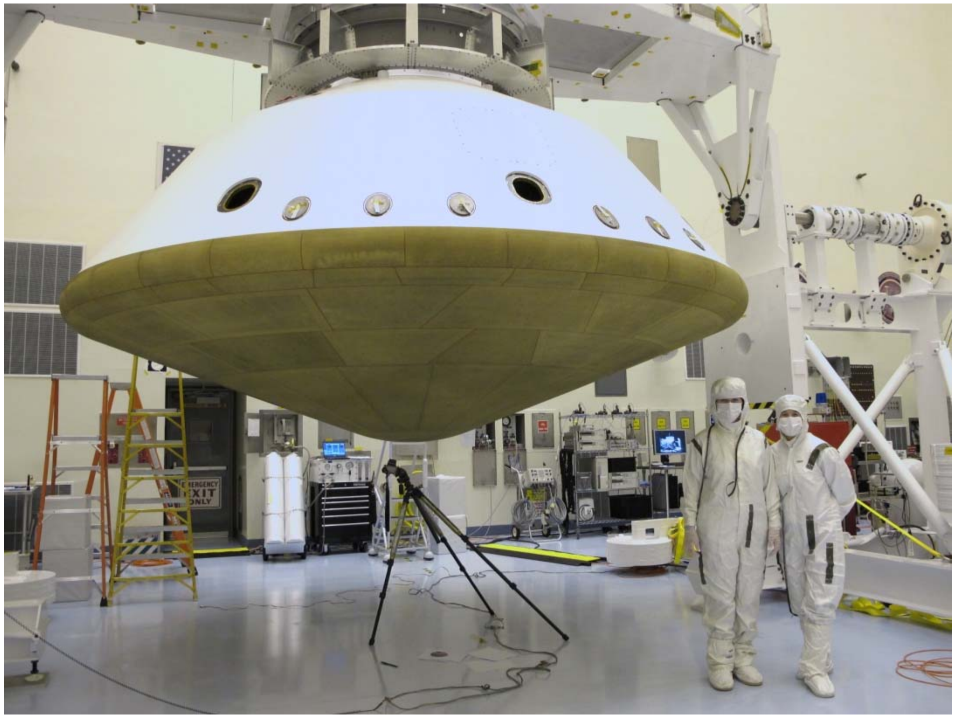
MSL Rover—not your father's rover!



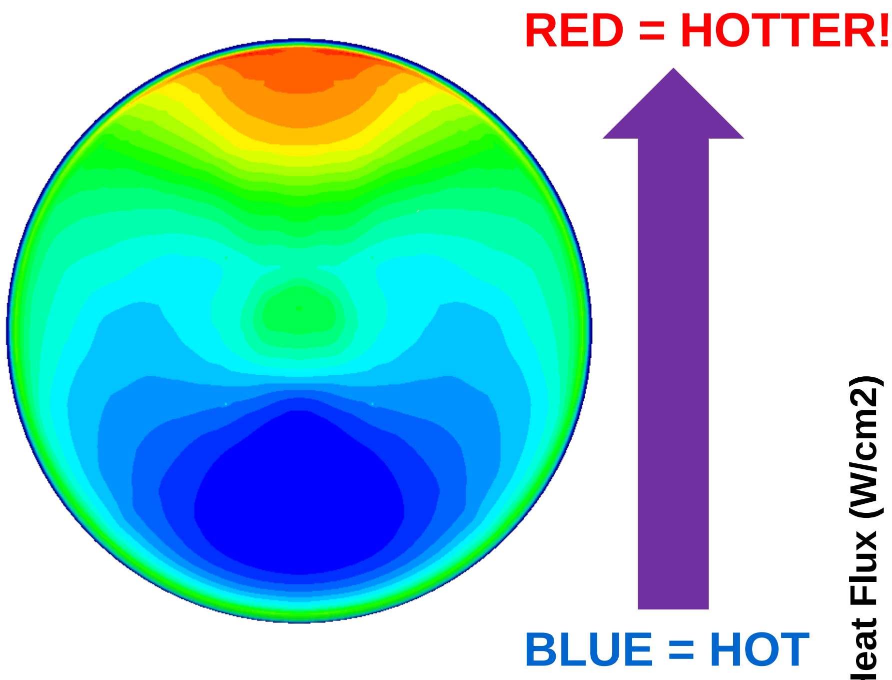
- 3 generations of rovers:
  - Curiosity (Mars Science Laboratory)
  - Spirit and Opportunity (Mars Exploration Rover)
  - Sojourner (Mars Pathfinder)

Mars Science Lab (MSL) Spacecraft



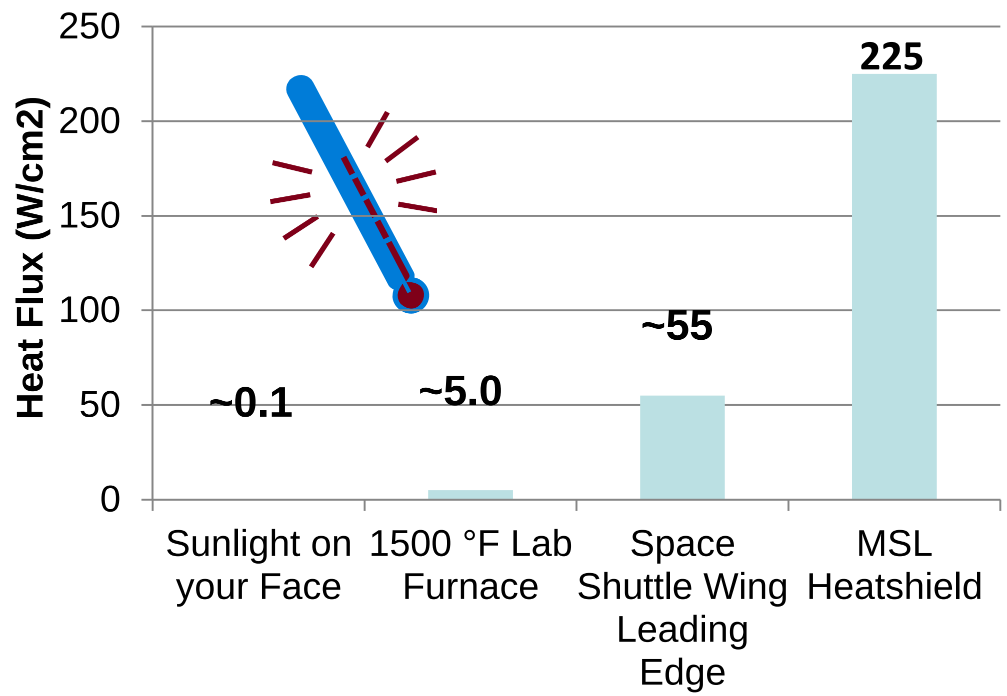


Heating Rates: How Hot is Hot?

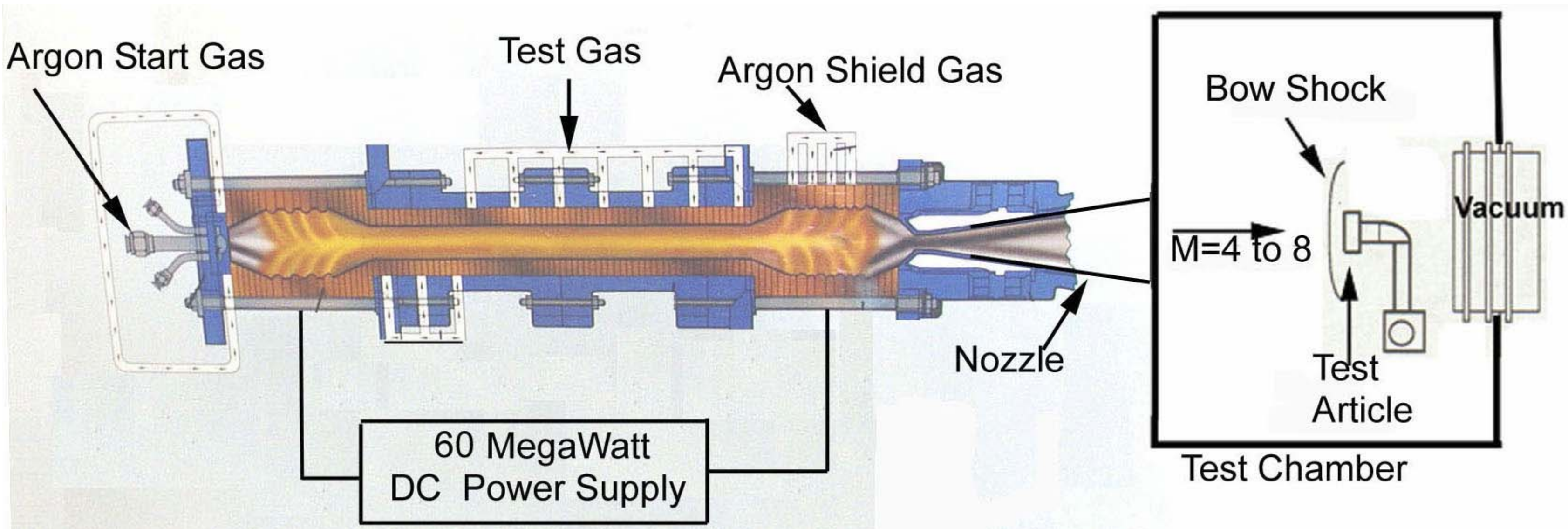


The MSL heat shield was designed to withstand the hottest spacecraft entry to Mars to date.

Comparison of heating rates



Arc Jet Testing For Qualifying Heat Shield Materials




Testing in Arc Jet


Before Test


After Test

Pushing the Boundaries of Heritage Material

- MSL's entry heating predicted to be more severe than previous missions, but it was hoped that the heritage material (SLA-561V) could still be used
  - SLA-561V flown successfully on **Viking**, Pathfinder, MER, Phoenix
  - *Material had worked well before, shouldn't it work well again?*
- Recognized that higher heating and shear testing needed
  - Material originally designed for Viking and an order of magnitude lower heating
  - Previous testing had focused on stagnation heating and no shear or turbulence
  - Concurrently, the human crewed vehicle program was exploring testing techniques to address these aspects—MSL partnered to take advantage of these tests

Coupon of SLA-561V

First Shear Test in Turbulent Duct

- Gouging due to glass melt-flow in the center of the coupon
- This is not a good look for you…but is it a material failure?

Material Failures During Shear Testing

- During the Project Critical Design Review with the NASA Administrator in attendance, it was announced that the heat shield material was being tested and situation was good
- Shear testing could cause disappearing material (“catastrophic failure”)
- After several months, team of experts could not conclusively find the “smoking gun”

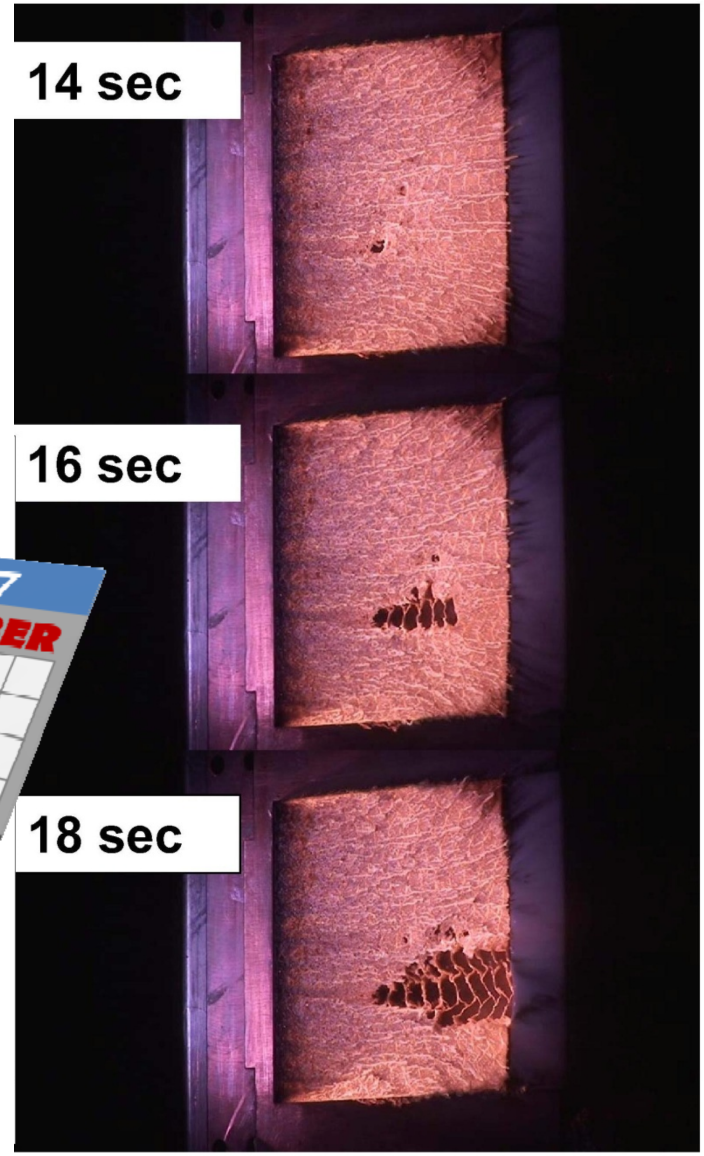
Initial Condition

Glass melt layer flows over sample and no failures observed

9 second ramp to final condition

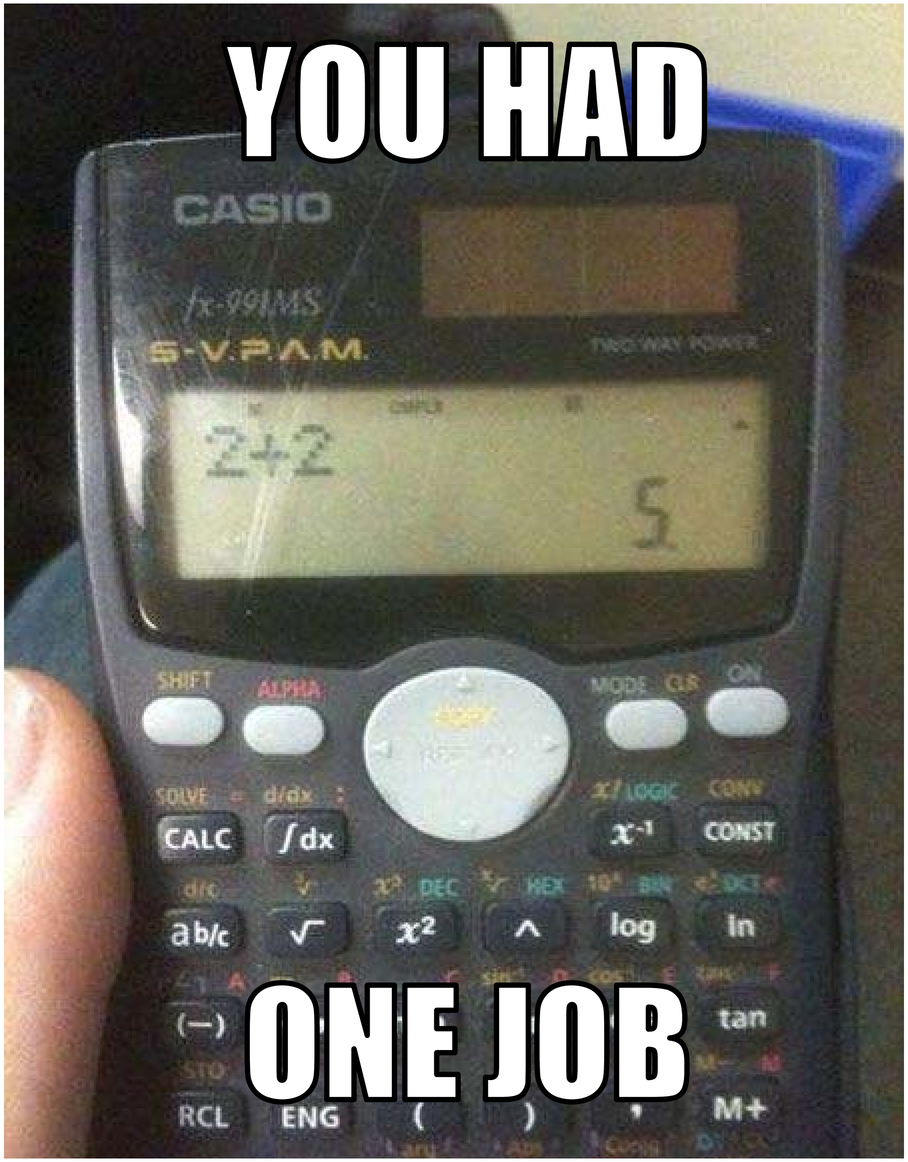
Increasing pressure but decreasing heating led to honeycomb cell “pop” and chain reaction of failures

NOW WHAT??!?



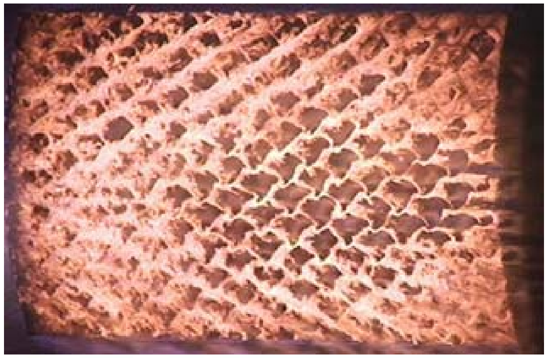
Video of Material Failure

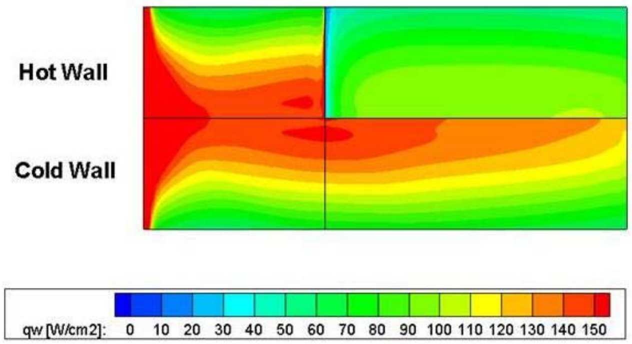
Not a Happy Time



Swept Cylinder Testing: Similar to Flight Conditions

Flow direction





- Failures also in swept cylinder testing, moderate environments:
  - q_{hw} ~ 120 W/cm^2
  - p ~ 0.22 atm
  - τ ~ 300 Pa
  - h ~ 14 MJ/kg
  - t = 3.4 sec! (YIKES!)

- High fidelity CFD calculations show peak heat flux occurs downstream
- Backup option—PICA, flown on Stardust, was undergoing further testing
- At same test conditions, PICA does not fail and shows no anomalous behavior

PICA and Gap Filler Perform Well!

T-2 Years to Launch: Decision Required!

- In order to support the manufacturing schedule for the flight heatshield, decision needed to make a 2009 launch
- Two options:
  - 1) Keep SLA-561V, but limit aerothermal environment to below glass-melt limit
  - 2) Switch materials, knowing time is the enemy (any other material would require significant development work for a 2009 launch)

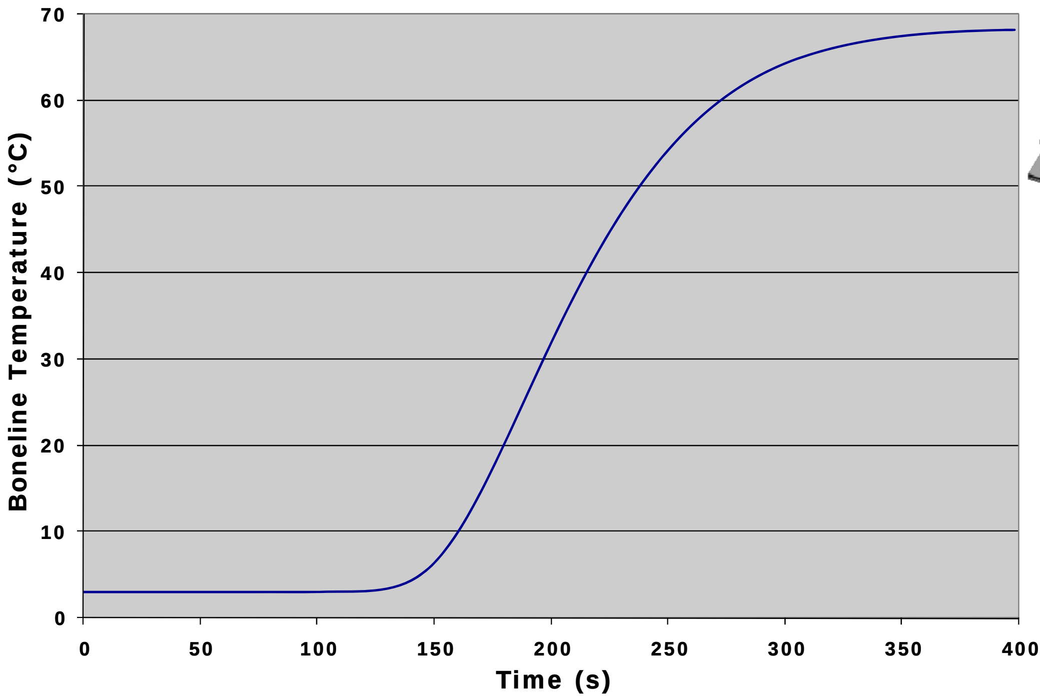
- Keeping heritage material would severely limit the overall mission:
  - Possibly limit landing sites (and thus negatively impact science objectives)
  - Adversely affect entry guidance robustness
  - Require more propellant
- Decision: Switch materials to PICA!
- Any shortcuts? (Orion, human exploration mission to Space Station and moon, was developing tiled PICA design)
- Unconventional method—design and build occurring simultaneously

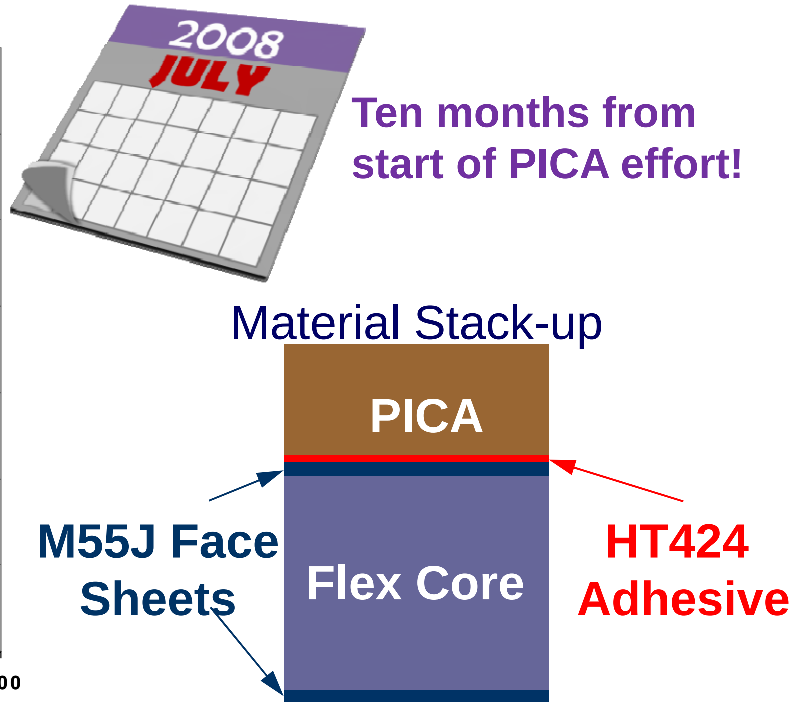
PICA in shear: well-behaved and no signs of failure

Run 5 q_{cw}=330 W/cm^2, P=32kPa, Grain 20°

- PICA material is robust at all tested conditions
- RTV-560 filled gaps perform well
- **IT DIDN'T BLOW UP!**

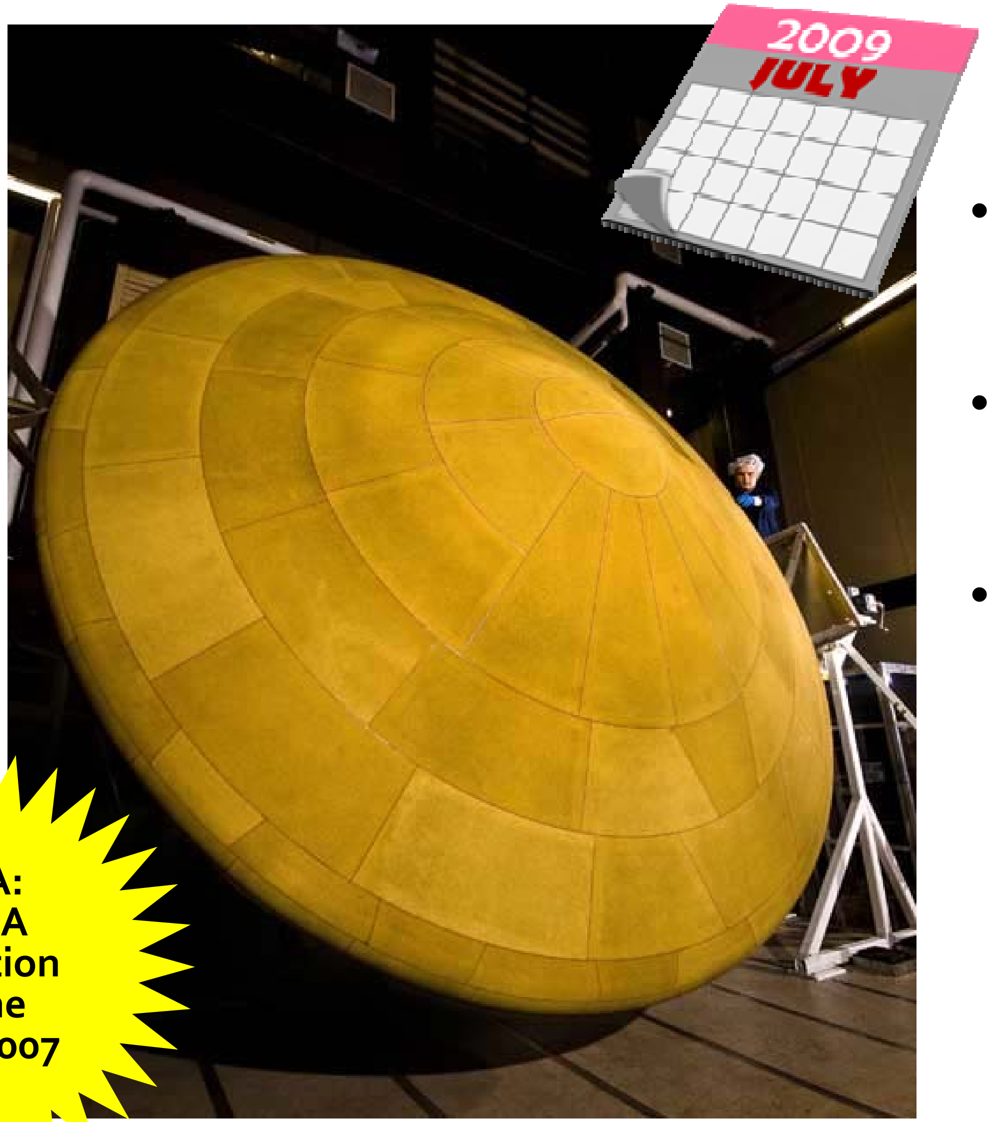
PICA Bondline Temperature Predictions





- Bondline requirement is maximum temperature of 250 °C, analysis predicted more than sufficient thermal margin (> 180 °C)
- Thermal model predictions at the region of highest recession indicate that the bondline temperature should reach a maximum of 70 °C during entry
- Analysis and margining process predict 0.94” required (vs 1.25” as-built), or 0.31” of extra material on heatshield

PICA Heat Shield



PICA: NASA Invention of the Year 2007

- 4.5 meters (~15 feet) in diameter
- Tiled design—first ever at Mars
- Although mission was delayed by 2 years, the heat shield was built in time for the original 2009 launch date

Photo of Heat Shield Being Ejected During Descent to Mars

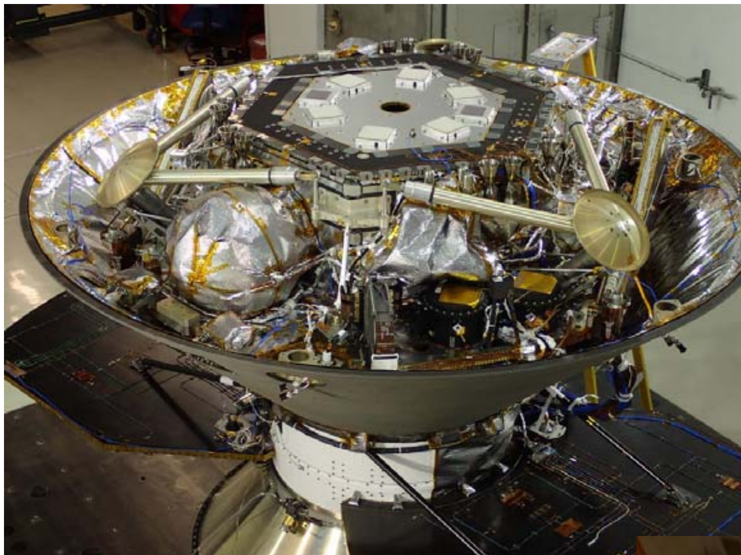
So What Did We Learn?

This isn't rocket science, it's brain surgery!

- It's vital to consider the operating environment for the design and early testing could save some heartache (and $$)
- Past success doesn't guarantee current success—***"It's always worked before"*** can come back to haunt you
- When the engineers are uneasy, you'd better listen to them


THE FOLLOWING PREVIEW HAS BEEN APPROVED FOR
ALL AUDIENCES

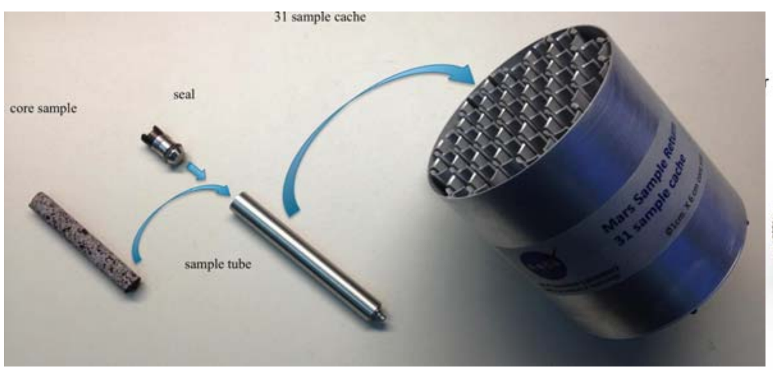
InSight Mission to Mars

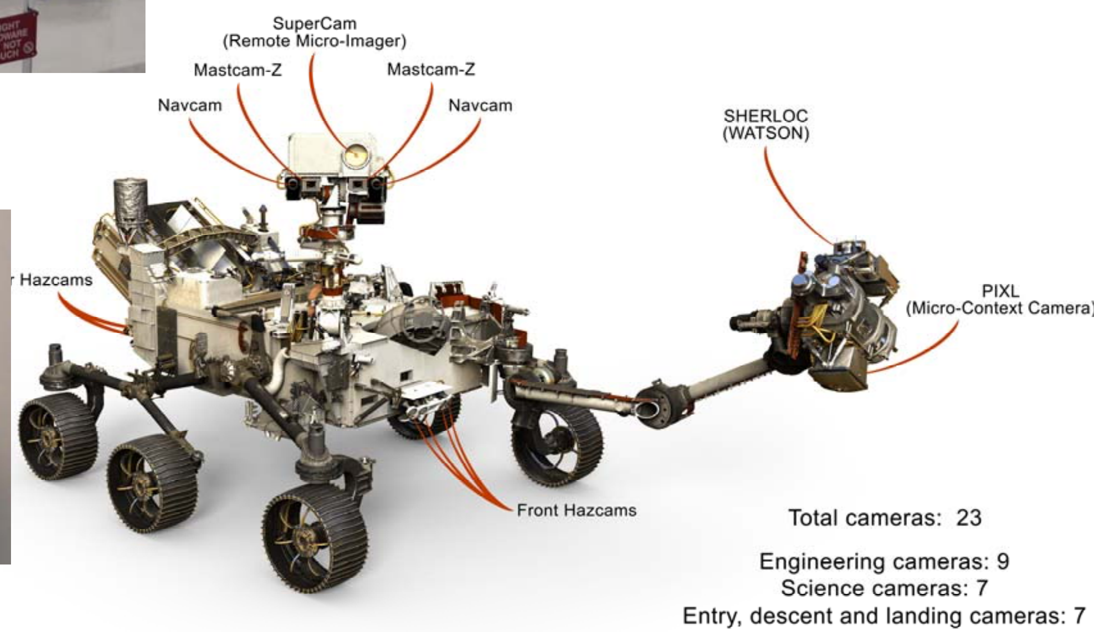


Launches May 5, 2018 out of Vandenberg Air Force Base!!

Mars 2020 is in the works…

Scheduled to launch July 2020. Stay tuned!





The MSL TPS Team

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  - Robin Beck
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  - Y.K. Chen
  - Anthony DeCaro (Eloret)
  - David Driver
  - Tahir Gökçen (Eloret)
  - Helen Hwang
  - Bernard Laub
  - Ed Martinez
  - Michael Olson
  - Dinesh Prabhu (Eloret)
  - Steven Sepka (Eloret)
  - Kristina Skokova (Eloret)
  - Chun Tang
  - Todd White (Eloret)
  - Michael Wright
  - ARC Arc Jet Team
  - CEV ADP Team
- Langley Research Center
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  - Richard Hund
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  - Kevin Makowski (ASI)
  - Katie Oakman
  - David Scholz
  - Jarvis Songer
  - Scott Stolpa
  - Joseph Vellinga
  - William Willcockson

Any Questions?

Our latest spacecraft concept (currently under development)