A Perspective on the Design and Development of the SpaceX Dragon Spacecraft Heatshield

by

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How Did SpaceX Do This?

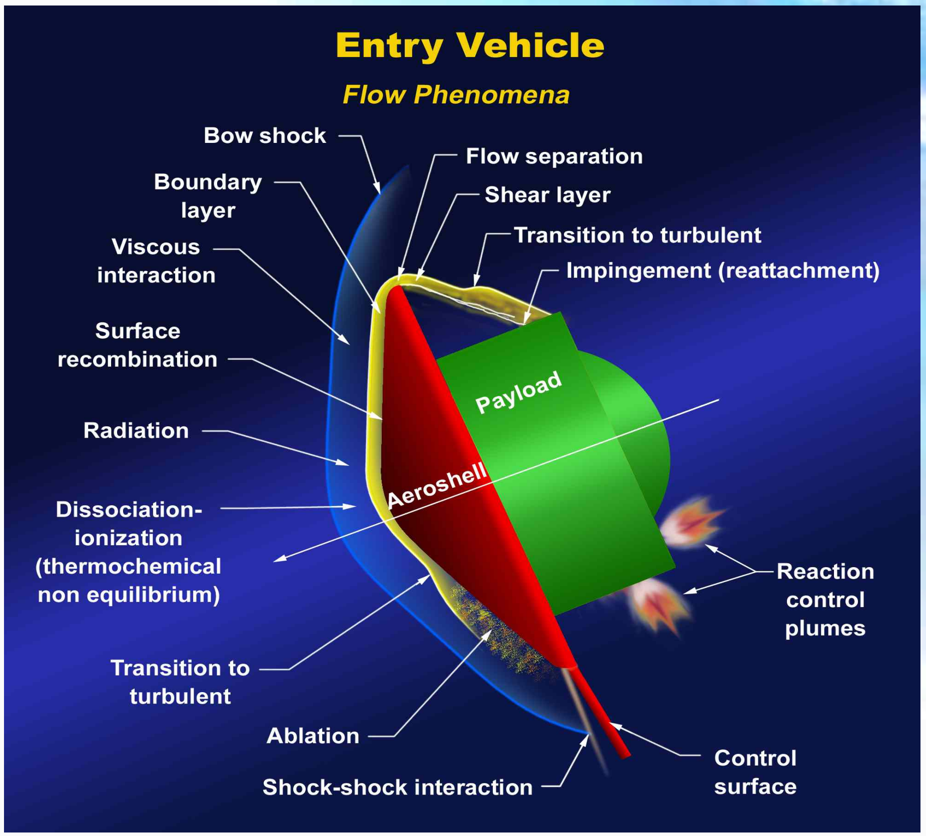
Recovered Dragon Spacecraft
After a "picture perfect" first flight, December 8, 2010

Beginning Here?

SpaceX Thermal Protection Systems Laboratory, Hawthorne, CA
"Empty Floor Space" December, 2007

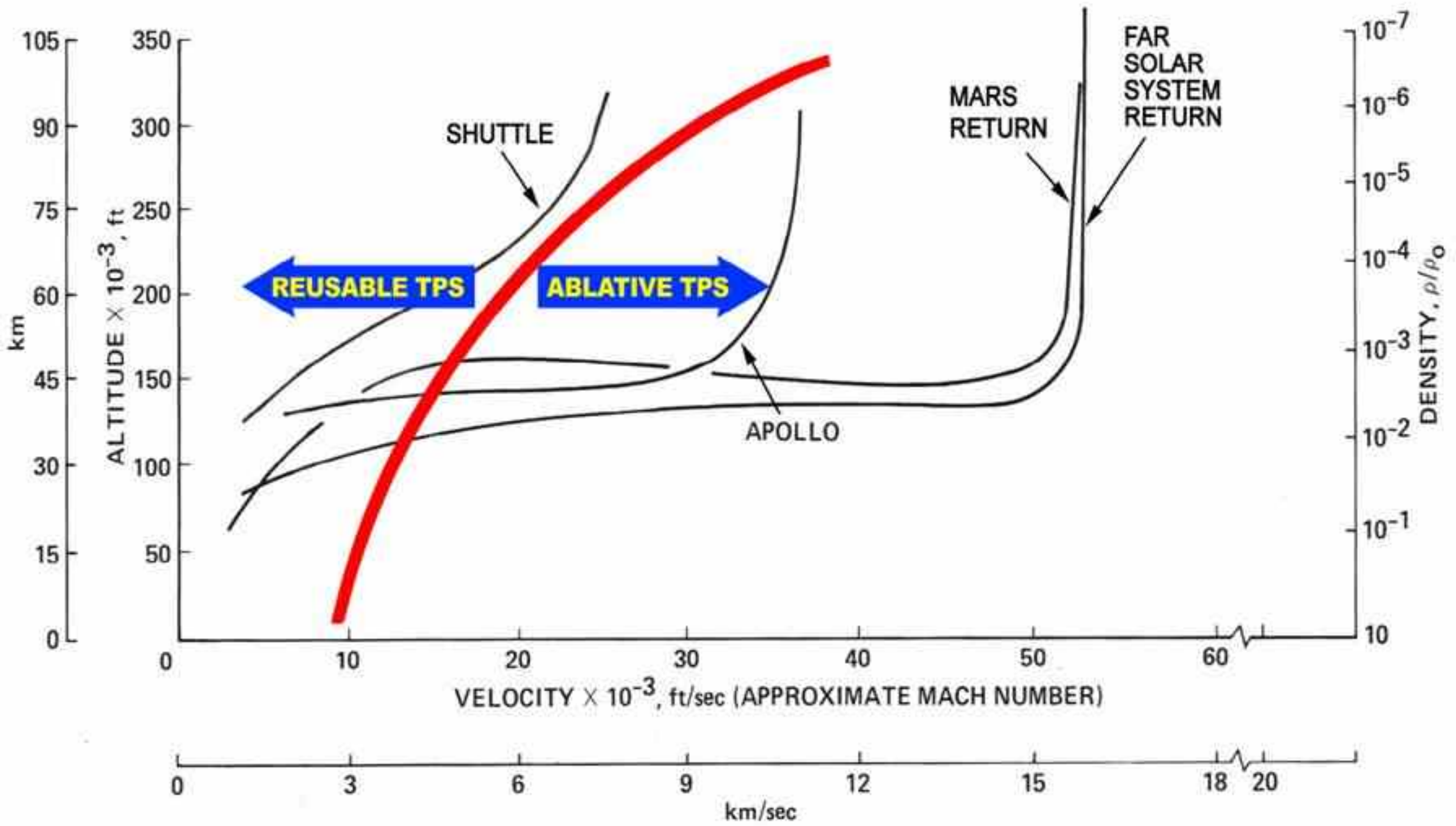
Some Necessary Background: Re-entry Physics

- Entry Physics Elements
  - *Ballistic Coefficient*
  - *Blunt vs sharp nose tip*
  - *Entry angle/heating profile*
  - *Precision landing reqr.*
  - *Ablation effects*
  - *Entry G'loads*
    - » *Blunt vs Lifting shapes*
  - *Lifting Shapes*
    - » *Volumetric Constraints*
    - » *Structure*
    - » *Roll Control*
    - » *Landing Precision*
  - *Vehicle flight and turn-around requirements*



Re-entry requires specialized design and expertise for the Thermal Protection Systems (TPS), and is critical for a successful space vehicle

Reusable vs. Ablative Materials



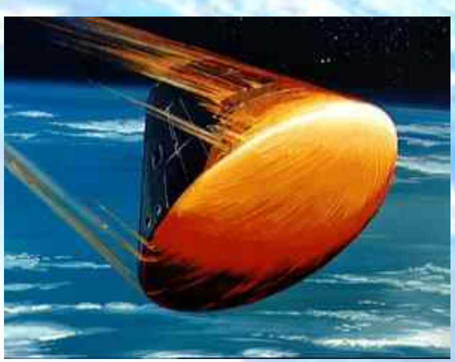
Historical Perspective on TPS: The Beginnings

- **Discipline of TPS began during World War II (1940's)**
  - ***German scientists discovered V2 rocket was detonating early due to re-entry heating***
  - ***Plywood heatshields improvised on the vehicle to solve the heating problem***

- **X-15 Era (1950's, 60's)**
  - ***Vehicle Inconel and Titanium metallic structure protected from hypersonic heating***
    - ***Spray-on silicone based ablator for acreage***
    - ***Asbestos/silicone moldable TPS for leading edges***
  - ***Spray-on silicone ablator found to be inadequate***
    - ***Unable to protect the vehicle beyond Mach 6***
    - ***Required considerable labor to refurbish***

Historical Perspective on TPS: Ablatives

- **Mercury/Gemini/Apollo (1960's)**
  - *Needed a lighter weight system than DoD re-entry body TPS of high density carbon or quartz phenolic*
  - *Developed polymer based moldable ablators with high temperature honeycomb reinforcement to withstand re-entry and lunar return environment: Avcoat 5026-39/HC-G for Apollo*
  - *Approximately 1/3 the weight of high-density carbon-phenolic*



- **Viking (1970's)**
  - *Apollo heatshield too heavy for Mars entry*
  - *Silicone based moldable light-weight ablator reinforced with a high-temperature honeycomb developed: super-lightweight ablator - SLA-561*
  - *Similar to Apollo TPS but lighter weight (~1/2 the density)*
  - *Good insulator with a robust architecture*

- **Pioneer-Venus, Galileo (1970's, 80's)**
  - *NASA did not have materials to handle severe entry conditions for the Venus or Jupiter entries*
  - *DoD developments in high density carbon phenolic used to meet mission requirements*
  - *NASA did not fully explore material payload impacts from use of DoD class heatshields*

Historical Perspective on TPS: Reusables

- **Reusable materials technology investment dominated TPS development efforts in the late 70’s through 80’s, 90’s and early 2000’s**
  - ***Shuttle:* Development of first reusable TPS**
    - ***Reinforced Carbon-Carbon (RCC), Ceramic Tiles (LI-900), TPS Blankets (FRSI & AFRSI), Refractory metals (Coated Niobium)***
  - ***NASP:* Investigation of advanced reusable TPS**
    - ***Ceramic Matrix Composites (CMC’s), Metal Matrix Composites (MMC’s), Actively Cooled Systems***
  - ***X-vehicles (X-33, X-37, X-38, X-43):* Development and investigation of more moderately advanced TPS**
    - ***Metallic TPS, Advanced Carbon-Carbon, CMC’s, sharp hypersonic leading edges, high-temperature tiles for leading-edges***

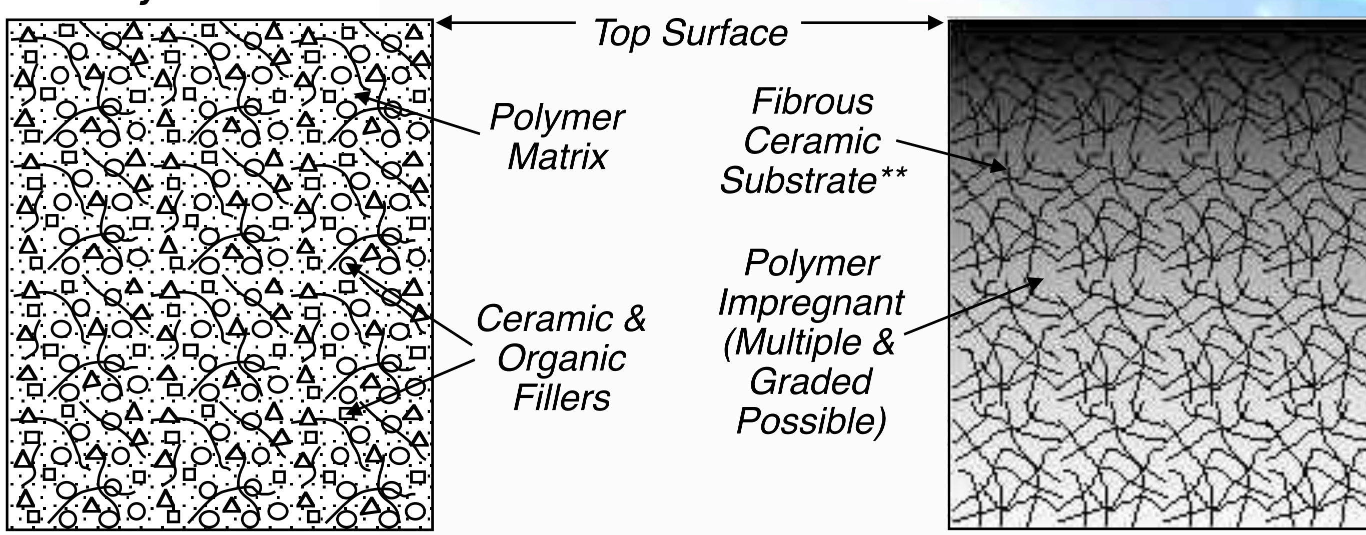
Ablative TPS Technology Development: Post Apollo/ Viking/ Galileo Era

- Lightweight Ceramic Ablators research initiated at Ames in the early 1990’s (Rasky, Tran)
  - Goal was to produce a new generation of ablators, making use of advancements in materials technologies
    - » ceramic substrates with polymer impregnants
  - Superior capabilities fit well with the Faster, Better and Cheaper philosophy
    - » adopted for Mars Pathfinder, Mars Exploration Rovers, Mars Science Laboratory, Stardust, SpaceX Dragon

A New Class of Ablators: Light-Weight Ceramic Ablators (LCA's)

Traditional Ablators*
Polymer Based

Light-Weight Ceramic Ablators
Ceramic Based



*(*e.g. Avcoat -5026, SLA-561V, Carbon-Phenolic)*

*(**e.g. silica, carbon, alumina fibers)*

Disadvantages:

- *Little strength at high temperature requiring reinforcing (e.g., honeycombs)*
- *Restrictive design and performance characteristics (e.g., thickness limits, pressure limits, heavy)*
- *Labor intensive manufacturing process, giving high fabrication costs and lot to lot variations*

Advantages:

- Good structural integrity at high temperature, avoids need for reinforcing honeycombs
- Multiple and graded polymer impregnants possible to optimize ablative and insulative performance (e.g., SPLIT)
- *Billet fabrication process giving a low cost, flexible, CAM compliant material*

Light Weight Ceramic Ablator Family

- **SIRCA**
  - Silicone Impregnated Refractory Ceramic Ablator
  - Uses flight certified ceramic substrates (Shuttle) and silicone impregnants (Viking)
  - Densities: 0.20 - 0.40 gm/cc
  - For heat fluxes < 300 W/sqcm
  - Patents 5,536,562 & 5,672,389
- **PICA**
  - Phenolic Impregnated Carbon Ablator
  - Uses Fiberform substrates from FMI, with flight grade phenolic impregnant
  - Densities: 0.25 - 0.60 gm/cc
  - For heat fluxes > 300 W/sqcm
  - Patents 5,536,562 & 5,672,389
- **SPLIT**
  - Secondary Polymer Layered Impregnated Tile
  - Used with either SIRCA or PICA to improve ablator effectiveness by augmented passive phase change and transpiration cooling
  - Densities: 0.25 - 0.80 gm/cc
  - Patents 6,955,853

SIRCA

PICA

Phenolic

PICA/SPLIT

PMMA

PICA Forebody for Stardust

Fastest entry ever of a spacecraft at Earth! (12.9 km/s) January 15, 2006

Post-Flight Stardust Sample Return Probe

Forebody design details:

- *Single piece Fiberform carbon substrate vacuumed formed to rough shape by FMI*
- *Substrate impregnated with phenolic, and then machined to final shape by FMI*
- *0.82 m diameter heatshield then integrated and bonded to spacecraft structure by LMA*
- *Qualified for Stardust entry environment:*
  - *Heat flux = 950 W/cm^2, Pressure = 0.45 atm, Heat load = 36 KJ/cm^2*
- *Significant impact crush capability demonstrated for hard landing after entry*

Great re-enty video: http://www.youtube.com/watch?v=H1JxIp2B7Jc

Stardust Capsule, including PICA Heatshield, on display at the Smithsonian National Air and Space Museum

- *Part of the "Milestones of Flight" Display*

Back to SpaceX…

- By 2007, SpaceX had selected PICA as their material of choice for the Dragon primary heatshield
  - Elon very impressed with Stardust performance and capabilities

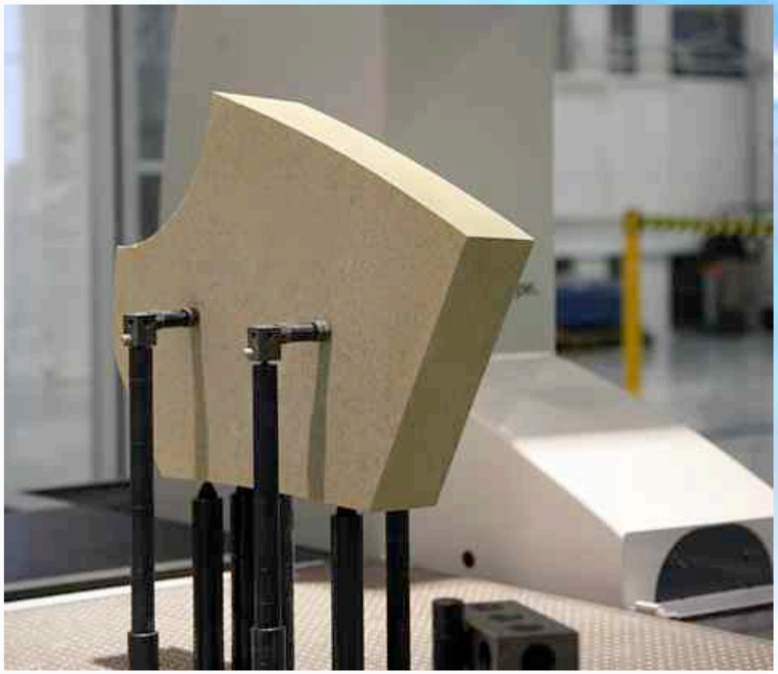
- Fall, 2007, Dr. Rasky approached by Elon Musk to help transfer PICA technology to SpaceX

Early Dragon primary heatshield mockup - 2007

- Spring 2008 through 2009, Dr. Rasky works closely with SpaceX (~1/2 time at SpaceX facilities) and other colleagues at NASA Ames to transfer PICA, and support Dragon heatshield design

Successful Tech Transfer of PICA

- Laboratory sized samples successfully made at Hawthorne
  - Spring 2008
  - A number of formula variations produced and investigated
  - Three different carbon fiber tiles substrates used
  - PICA-X formulation established by fall, 2008

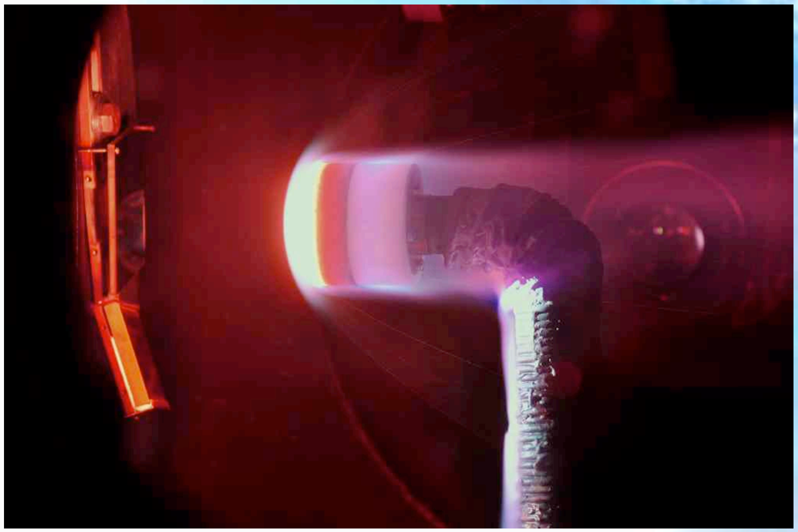


PICA-X undergoing inspection

- Full size production billet of PICA-X demonstrated
  - Prototype produced in fall, 2008
  - Using a custom designed vacuum oven with very precise thermal control (both spatially and temporarily)

Test Validation of PICA-X

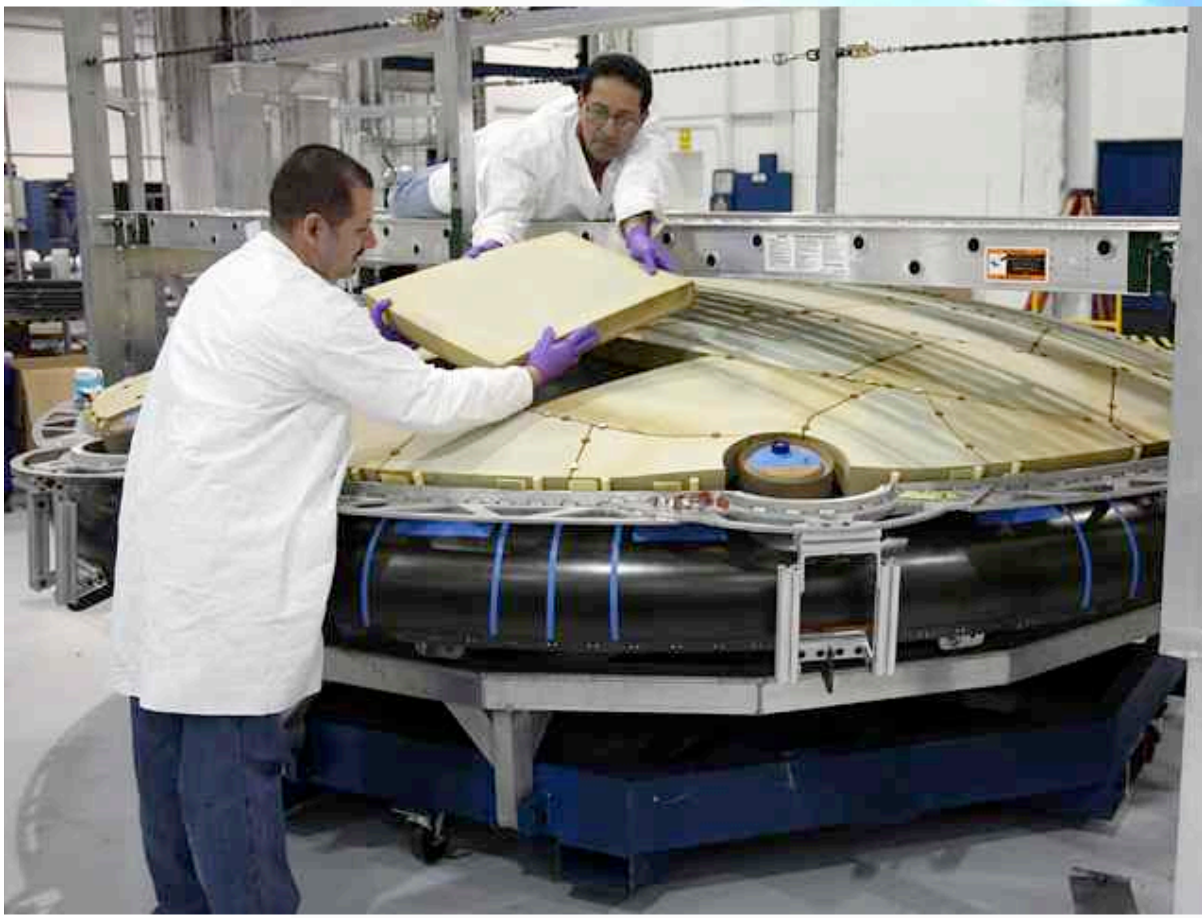
- PICA-X successfully certified for flight
  - Very successful arc-jet test series conducted at NASA Ames in December 2008
  - Three different carbon-fiber substrate PICA-X versions tested
  - All performed above expectations



Successful certification arc-jet testing at NASA Ames – December 2008

- Production capability established
  - Batch processing for PICA-X demonstrated by fall 2009
  - Ability to produce PICA-X in excess of that needed for Dragon

PICA-X Installed on Dragon



- PICA-X being installed on Dragon carbon-composite carrier structure, 2010

PICA-X Heatshield Installed on Dragon, 2010

Dragon Integrated to Falcon-9

Dragon/Falon-9 Ready for Roll-out

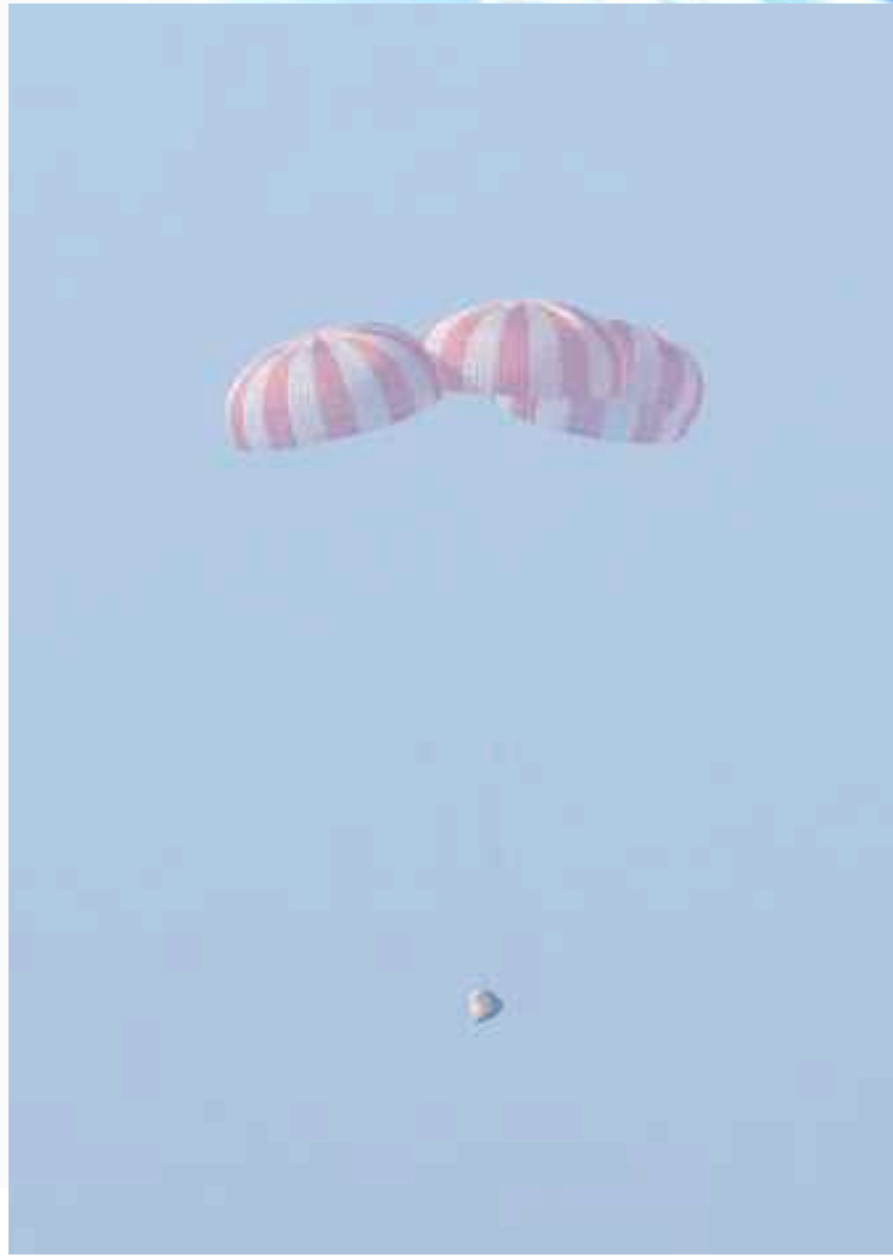
Dragon/ Falcon-9 Ready for Launch

Dragon/ Falcon-9 Launch

- ***December 8, 2010***

Dragon Re-entry

Dragon Descent



Dragon Recovery

Recovered Dragon Spacecraft

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And importantly, by using a different business model than traditional government aerospace

(a potential game changer)

Traditional Government Aerospace Business Model

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- ***Modeled on military organizational approaches:***
  - ***Hierarchal, with chain of command***
  - ***Much more focus on control than on efficient use of resources***
  - ***Rely on a large cadre of internal experts and unique facilities***
  - ***Form key alliances with customers, stake holders and specialized suppliers***
  - ***Follow a fairly rigid requirements driven design approach***

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- ***Prefer "Cost-Plus" contracting with the government***
  - ***Covers contractors costs, plus a small profit (~6-7%)***
  - ***Provides flexibility for the government to change requirements***
  - ***Both contractor internal and supplier cost increases can be passed onto the government customer***

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  - *Both contractor internal and supplier cost increases can be passed onto the government customer*
- ***Proven record for producing custom, complex hardware and systems***
  - ***With very high performance and reliability***
  - ***That have national security functions or implications***
  - ***Where cost often is not a driver***

SpaceX Business Model

SpaceX Business Model

- ***Adopted from the Software Development industry:***
  - ***Where Elon got his management and development experience***
  - ***Very flat organizationally***
  - ***Broad and organic collaboration and communication***
  - ***Rely extensively on the internet for technical data, product data, and procurement of equipment and services***
  - ***Must have multiple suppliers for any critical path components, or will bring in-house***
  - ***Design approach is collaborative and pursues crawl before you walk before you run development strategies, rapid prototyping, and identification of low-cost approaches that allow iterative improvement***

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- ***Prefer "Fixed Price" contracting with customers***
  - ***A fixed price for a fixed set of produced hardware and/or services***
  - ***Minimizes customer requirement changes & insite/oversite***
  - ***Allows for considerable potential profit***
  - ***Relies on very good internal and supplier cost control***

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  - *Relies on very good internal and supplier cost control*
- ***Goal is to produce hardware and services at large scale***
  - ***For use by government and the general public***
  - ***With very good performance margins and real world use to ensure acceptable operation***

Will the SpaceX Business Model Continue to Provide These Extraordinary Results?

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Too early to say

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But it certainly is interesting

And quite a contrast to most of our recent experience with Space

What will SpaceX do next??

What will SpaceX do next??

Perhaps help take us to the Moon and Mars…

Questions

Backup Slides

Historical Perspective: Ablative TPS

- **TPS Investment in the 60's - Focused Program - Technology development with specific mission goal**
  - Material Performance, Heat Shield System Development and Design Architecture
  - Test, Test and more Test
  - Ground and flight test => Material behavior, Analytical capabilities and model development

- **Apollo 1960's - 1970' Avcoat 5026-39/HC-G**
  - Developed honeycomb system due to reliability risk of tiled approach
    - » Needed a lighter weight system compared to DOD TPS (Carbon- or Quartz Phenolic)
  - Too heavy for Mars entry - Viking

- **Viking (1975) SLA-561**
  - Used low density silicone in honeycomb - similar to Apollo TPS
    - » Good insulator with a robust architecture

- **Pioneer-Venus, Galileo**
  - NASA didn't have materials to handle entry conditions
  - DoD investment in carbon phenolic leveraged to these missions
  - But, NASA did not fully explore material performance limits due to facility capability (e.g., spallation on Galileo)

Commercial space is an important and growing segment of the US space industry...

...NASA under Gen Bolden will actively support and advocate its development.

Scaled Composites

SpaceX

XCOR

Blue Origin

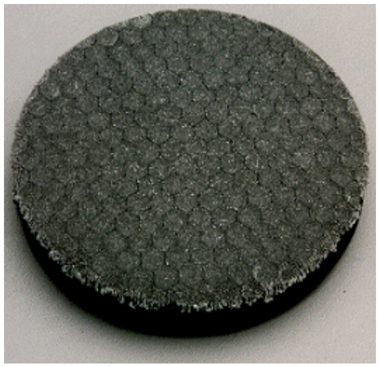
Orbital Sciences

LCA Development History

- **Light-weight Ceramic Ablators (LCA's), were conceived and developed at Ames starting in in the early 1990's**
  - Concept based on Ames' expertise in low density fibrous ceramic substrates
    - » Developed several fibrous ceramic substrates for TPS used on the Space Shuttle (AIM-22, FRCI-12, AETB-8)
  - Combined with expertise and advances in ceramic polymer precursor technology over the past 20 years
    - » Selected polymer(s) impregnated into a suitable fibrous ceramic substrate
    - » Innovative impregnation techniques developed at Ames to maintain low density and good thermal properties
  - Approach maximizes ablation and thermal performance, and minimizes fabrication costs

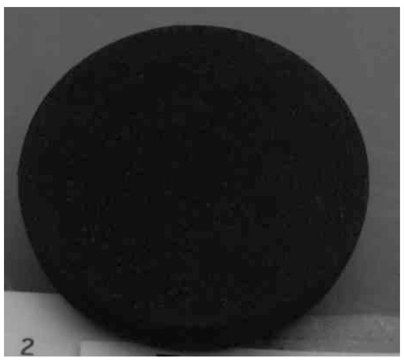
PICA Forebody for Stardust

Arc-Jet Testing at Reference Sample Return Entry Conditions
(q_{cw} = 400 W/cm^2, P_{stag} = 0.25 atm, q_{load} = 24 KJ/cm^2)



Avco-5026

Apollo Shield - Heavy, with Substantial Recession and Mass Loss

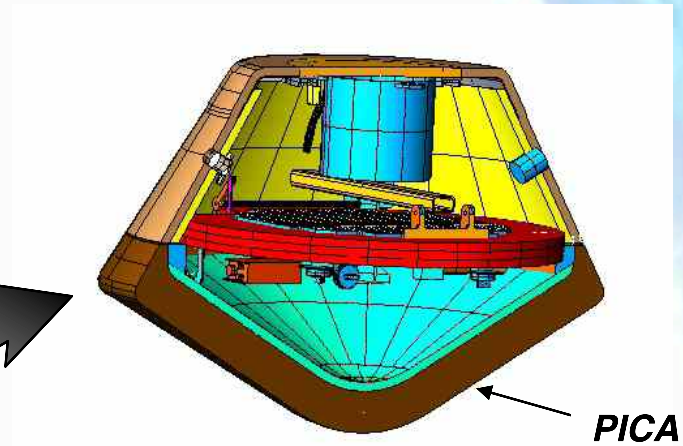


PICA-15

New PICA material - Lighter Weight with Reduced Recession and Mass Loss

***PICA** (Phenolic Impregnated Carbon Ablator):*

>> Base lined by Lockheed-Martin for the Stardust fore body (single piece) heat shield



Stardust Sample Return Probe

Significantly Improved Capability, Reduced Weight and Cost Compared to Apollo Era Materials - Enabling Technology for Stardust

PICA Material Performance

Stardust Cored Sample

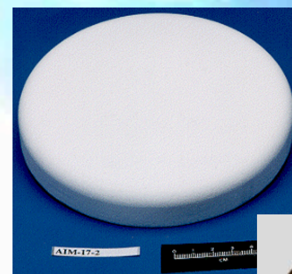
Phase I Arcjet, 1000 W/cm^2

Phase I Arcjet, Dual-pulse

Phase I Arcjet, 130 W/cm^2

Historical Perspective on TPS: New Ablators, Tiles and Advanced Blankets

- **Modest budget level research and development continued on ablators (1980's, 90's)**
  - *Light-Weight Ceramic Ablator work at NASA Ames*
    - » *Ceramic substrates with polymer impregnants, yielding several useful systems (PICA, SIRCA, SPLIT, Black Tile)*
  - *Polymer based ablator development at Applied Research Associates*
    - » *Derivatives of Viking Super-Lightweight Ablator (SLA)*
  - *Silicone ablator development at ITT Industries (formerly Acurex/Aerotherm)*
    - » *Acusil line of moldable TPS products*



- **Modest budget level research and development on tile and blanket TPS (1980's, 90's)**
  - *Higher temperature tiles (AETB) with tougher coatings (TUFI, TUFROC) at NASA Ames*
  - *Higher temperature quilted blankets (Nextel fabrics, Silicon-carbide fabrics, Saffil batting) at NASA Ames*
    - » *Silicon-carbide fabrics found to be a health hazard*
  - *Toughened metal (DuraFRSI - NASA Ames) and ceramic coatings (CRI - Boeing) for blankets*
  - *Higher temperature felts blankets (PBI, PBO, carbon) at NASA Ames*