Paolo Santini's Memorial Lecture

Ablators: From Apollo to Future Missions to Moon, Mars and Beyond

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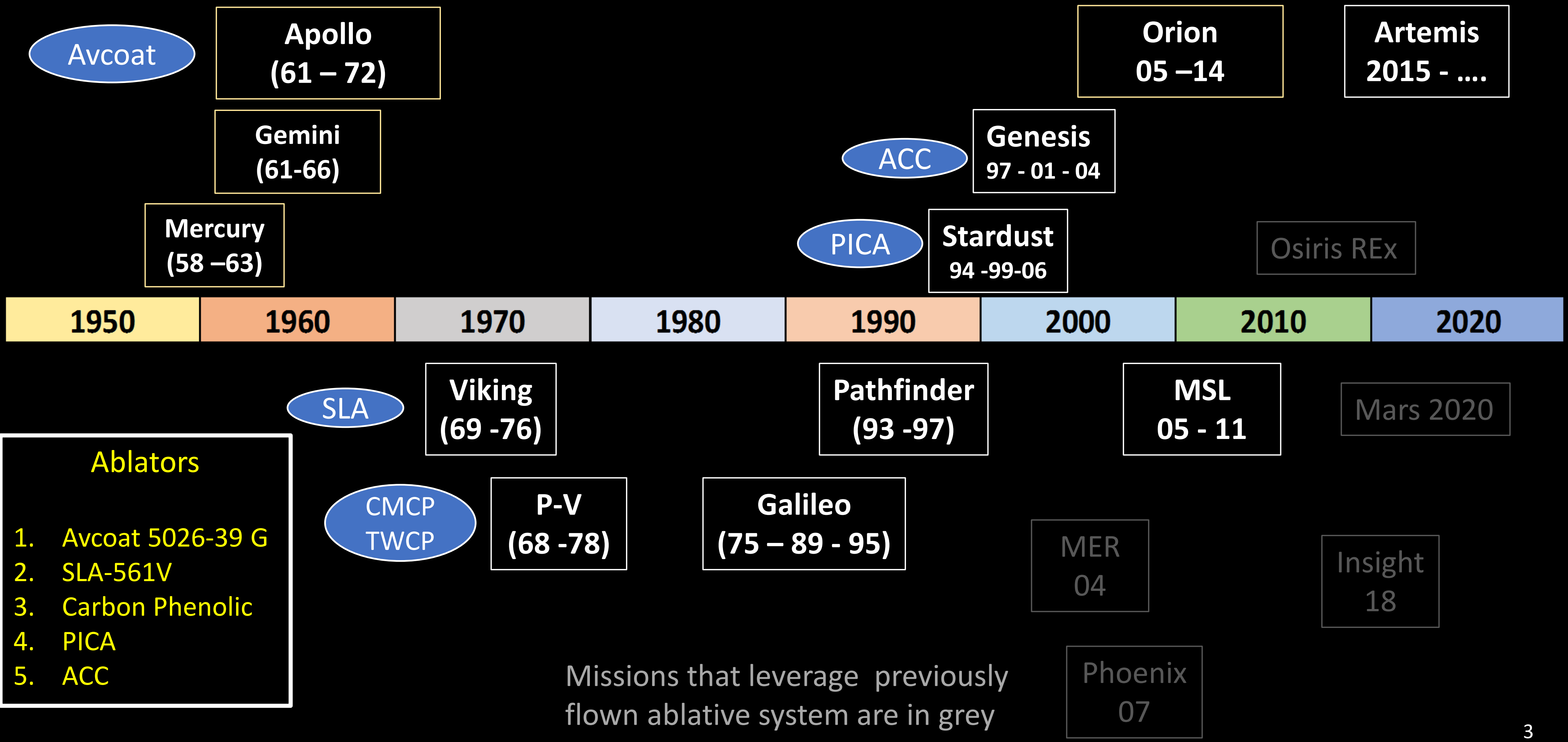
What is this talk about?

- Brief History of ablators
  - Pre-Apollo (50’s and 60’s)
  - Apollo (60’s and 70’s)
  - Mars, Venus and Jupiter (70’s and 80’s)
  - Small Missions in the era of “ Faster, Cheaper, Better” (90’s)
  - Moon , Mars and Beyond (2000 – 2030)
- Concluding remarks

History of Ablators:



Ablators

1. Avcoat 5026-39 G
2. SLA-561V
3. Carbon Phenolic
4. PICA
5. ACC

Missions that leverage previously flown ablative system are in grey

Pre-Apollo, Pre-Gemini and Pre-Mercury

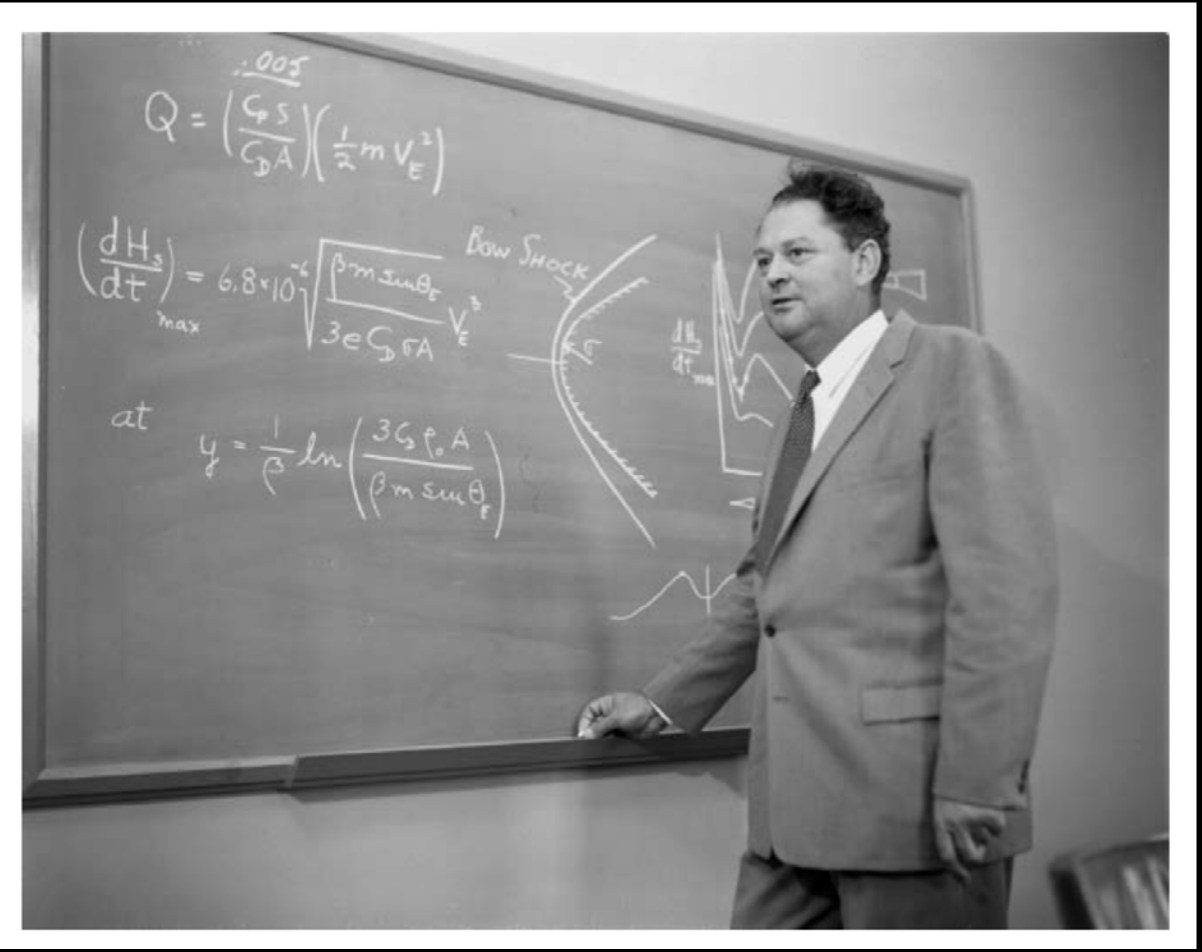
Discipline of TPS began during World War II (1940's)

- 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,)

- 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

Blunt Body: A Revolutionary Concept with Ablative TPS Solution to Hypervelocity Entry

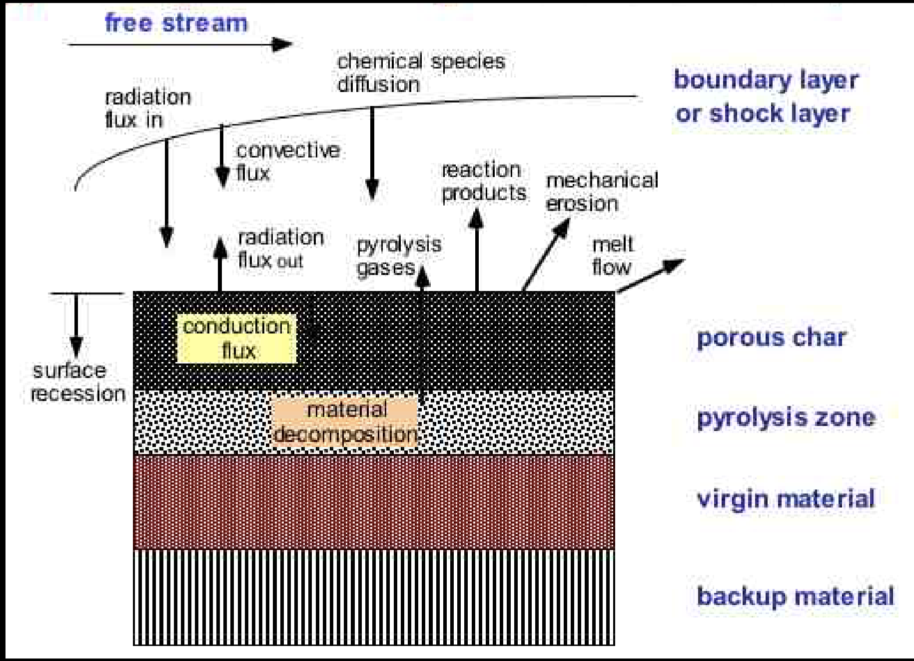


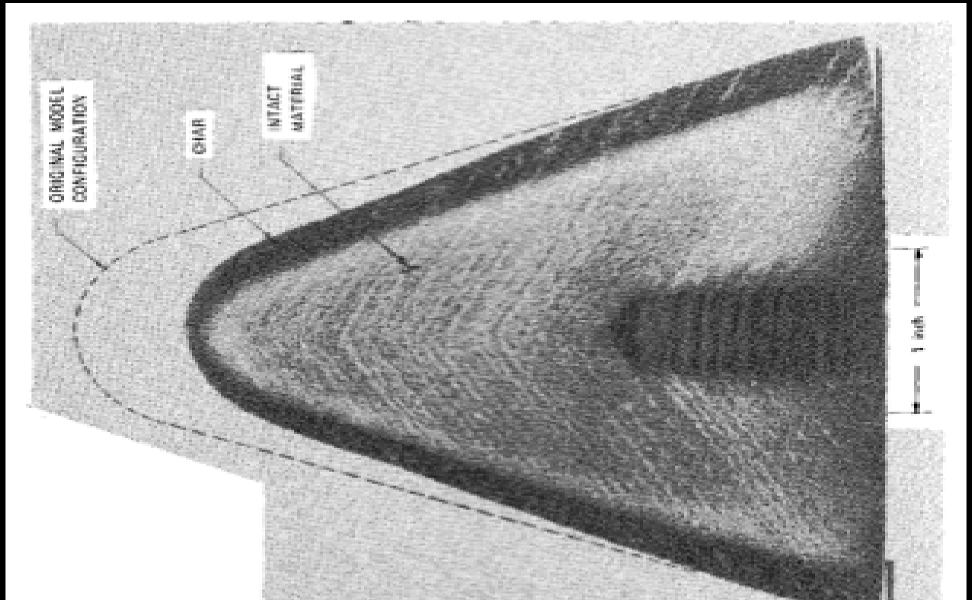
Harvey Allen (1952), Blunt-body Concept for surviving Hypersonic Reentry

“Half the heat generated by friction was going into the missiles," recalled Harvey Allen.

"I reasoned we had to deflect the heat into the air and let it dissipate. Therefore, streamlined shapes were the worst possible; they had to be blunt."

Ablative Thermal Protection System(1950's)



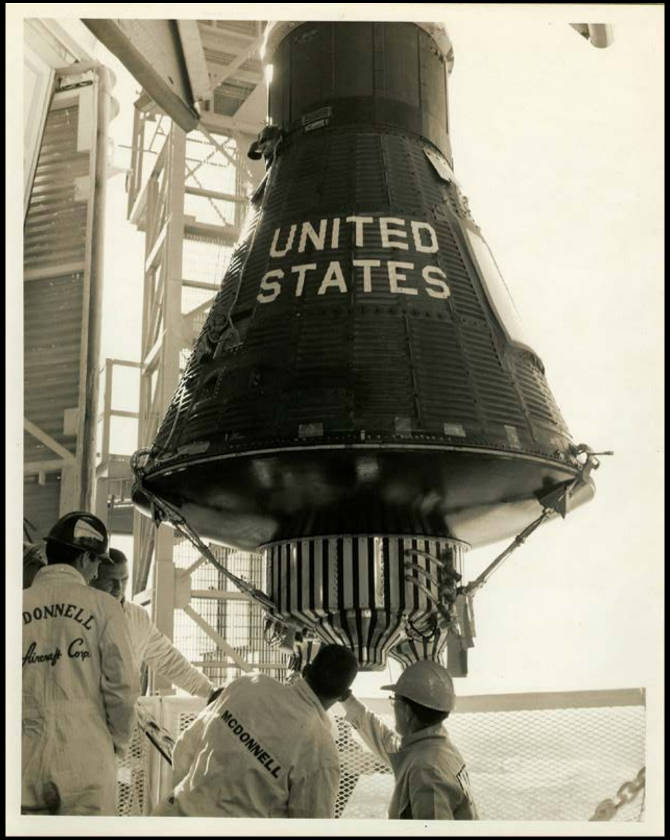


From: G.W. Sutton AIAA 82-4038.

Post arc-jet test article
Wrapped Silica-Phenolic (1958) (1 inch base)

- Test as you fly ??? – Facility capabilities are limited – Cannot test full scale or flight profile
  - Arc jet testing is limited to small article size (typically < 4" for > 1000 W/cm^2)
- Ablator sizing is done using high fidelity thermal response models, validated with limited data.
- System certification will continue to remain a challenge

Mercury (1959 – 1963) 20 Un-crewed and 6 crewed flights 1.9 m heat shield – Peak heating ~ 50 W/cm2

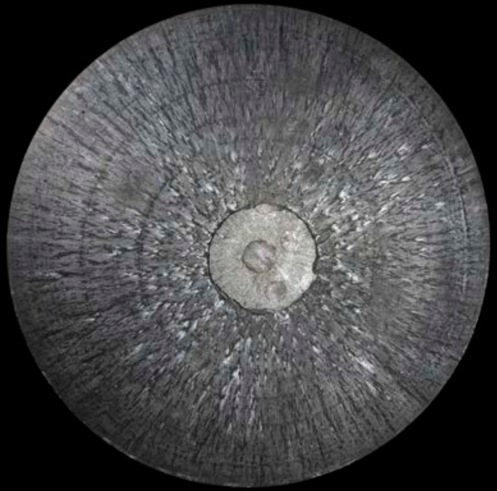


- January, 1959 - thermal protection options
  - Beryllium heat sink or an ablator.
- Fiberglass-phenolic shingles for the heat-shield.
  - Beryllium and Rene metallic for the conical sections
- Feb 20, 1962: John H. Glenn Jr. became the first American to orbit the Earth on Mercury.

System Integration:

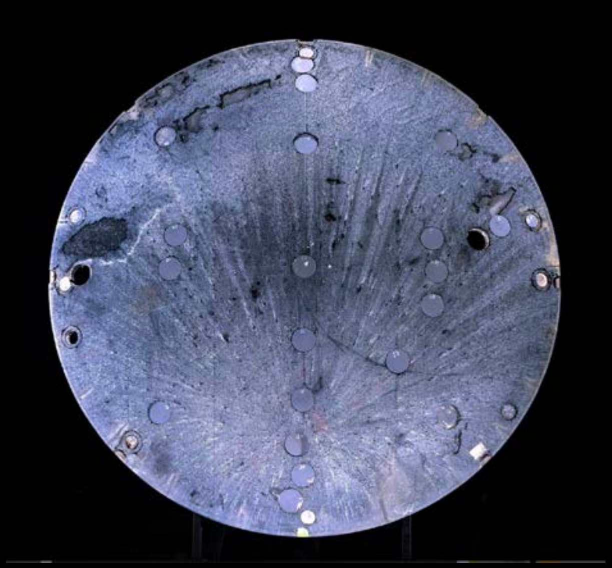
  - Early test heatshield separation resulted in recontact – Decision was made to keep the heat-shield intact
  - Retro rockets attached to the heat-shield.
  - Water impact landing

- Manufacturing
  - Heatshield center plug did not bond well and kept falling off on most manned flights.
  - Center plug missing on Friendship 7. Number of cracks in HS exterior, did not compromise mission safety.



Heat shield sample from Scott Carpenter's "Aurora 7" spacecraft (May 24, 1962) (Smithsonian collection)

Gemini (1961 – 1966) 2 Un-crewed and 10 crewed flights
3.05m heat shield – Peak heating ~ 60 W/cm2



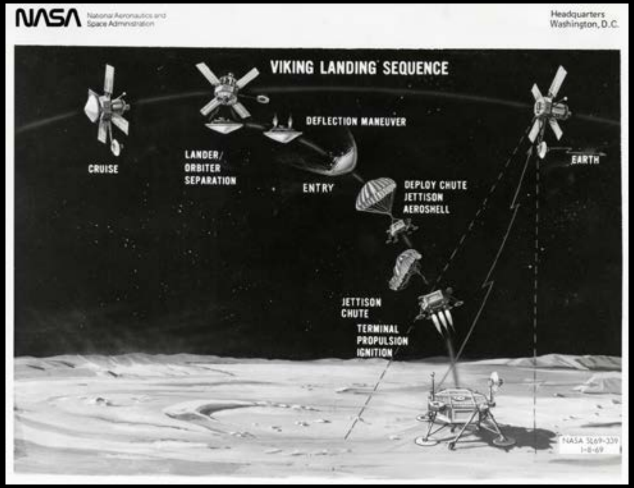
- Ablative material is fiberglass honeycomb filled with silicone elastomer.
  - Corning DC 235 Silicone elastomer
- Honeycomb bonded to the structure allowed attachment verification
- The ablative substance is a paste-like silicone elastomer material which hardens after being poured into a honeycomb form.
- Room temperature cure
- Virgin white surface turns black as a result of charring.
- Glass forms at the surface e during heating and melt flow

Heat shield fragment from the Gemini VIII, which carried astronauts Neil Armstrong and David Scott into Earth orbit on March 16, 1966

Apollo (1961 - 1972) 16 Un-crewed and 11* crewed flights 3.91 m heat shield – Peak heating ~ 600 W/cm2

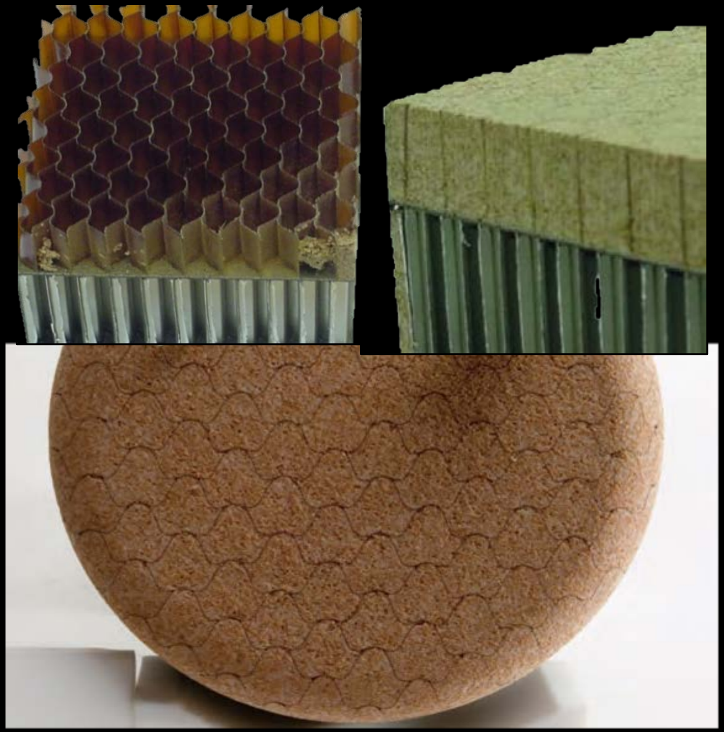
- Avco Corp. developed the ablative material, and the heat shield manufacturing process in 3 years.
- Avcoat 5026-39G. Epoxy-novalac resin reinforced with quartz fibers and phenolic micro-balloons in a phenolic honeycomb
- 360,000 cells. Avco invented a way to fill each of the cells by hand and developed repair procedures.
- Qualified for In-space thermal environment of (-260^{0}F - + 250^{0}F)
- Impact of Micro-meteor were assessed
- Forebody penetration (Compression pad) and other singularities

Viking Landers (1976) 2 Landers – Delivered from Orbit 3.5m heat shield – Peak heating ~ 26 W/cm^2



InSight Heat Shield Assembly – Photo: Lockheed Martin

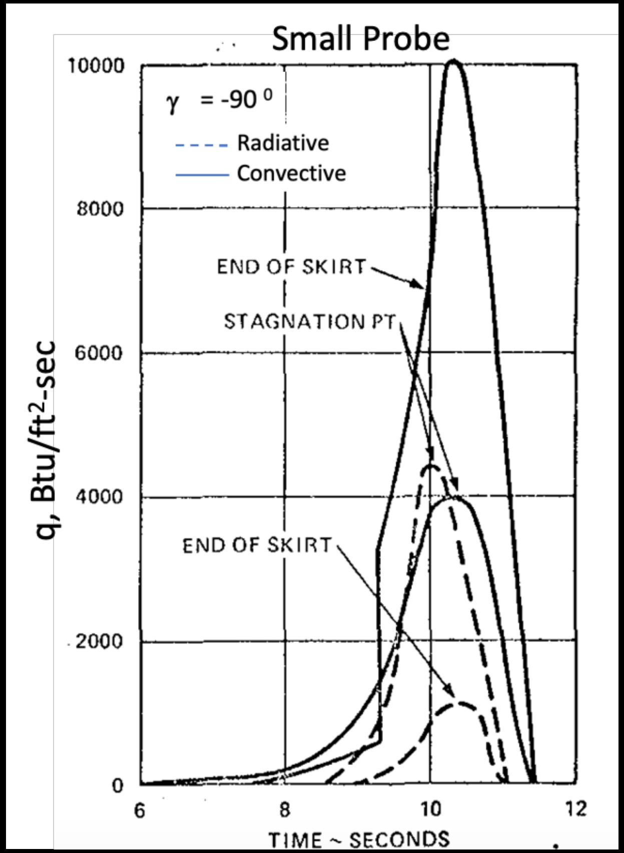
- Apollo heatshield too heavy for Mars entry
- Super-Lightweight Ablator - SLA-561
- Similar to Apollo but lighter (~1/2 the density)
  - Good insulator
- Developed in the late 60’s by Martin Marietta (now L-M)
- Testing showed robust performance
  - In space environment, vibro-acoustics, thermo-structural, thermal
- Manufacturing
  - Could not use Apollo “gunning” – hand packing
- Planetary protection requirement



Pioneer-Venus (1978) 3 Small (0.76 m) and 1 Large (1.52 m) Probes
Peak design heat flux 10 kW/cm2 at 10 atm. pressure

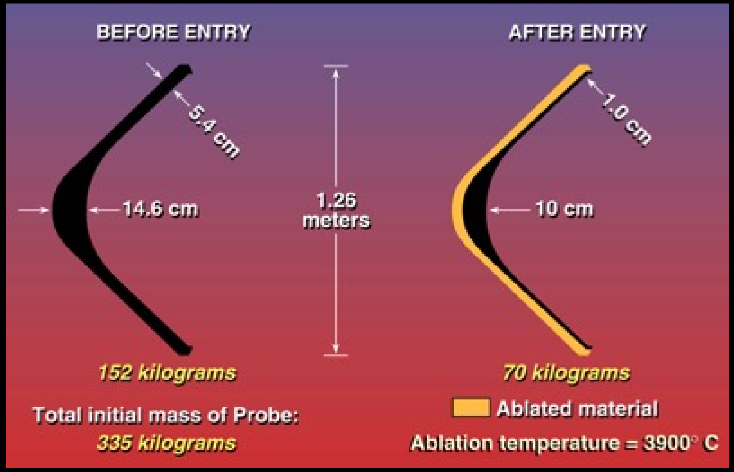
Pioneer-Venus:

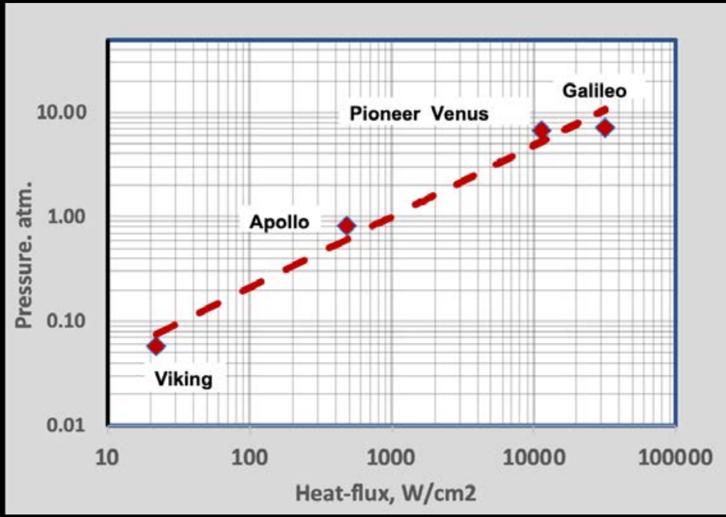
- 4 probes (3 small and one large)
- Shock layer radiation dominated (much more severe than Apollo)
- Both convective and radiative more than an order of magnitude higher than Apollo
- NASA did not have materials to handle severe entry conditions for the Venus
    - Reflective material (Teflon) considered but rejected
    - Phenolic-Nylon vs Carbon-Phenolic
    - Carbon-Phenolic tested in air and CO_2
- GE (Valley Forge) developed high density carbon phenolic, two-piece, heat shield (1975)
    - Two different manufacturing , nose and frustum with Chop-Molded and Tape-Wrapped carbon phenolic
    - Tape-wrapped derived from DoD



Galileo (1995) - Single Probe Entry at 47.4 km/sec Peak conditions (30,000 W/cm2 and 7.3 atm)

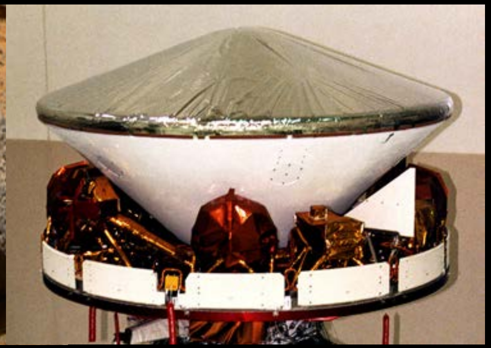
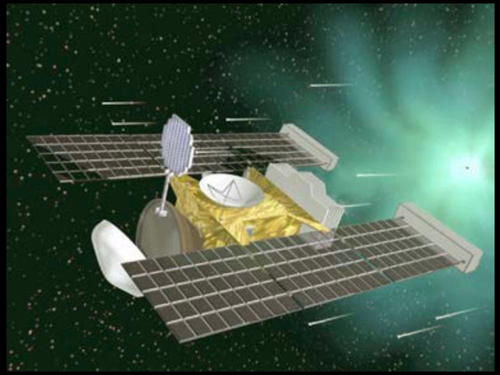
- Predicted heating at ~ 49 km/sec entry – extreme
  - **Galileo peak heat-flux exceeded the heating at the nose tip of a ballistic missile and the radiative heating from a thermonuclear explosion combined.**
- GE Carbon Phenolic (2 piece) chop molded and tape wrapped heat shield manufacturing from P-V.
- Heat shield mass was 50% of entry mass.
- Recession Sensors in the heat shield provided data
- In 15 sec., 50% of the heat shield ablated
- Margined design proved to be non-conservative on the shoulder – near failure
- Based on flight measurement, margined TPS will be 70% of the entry mass





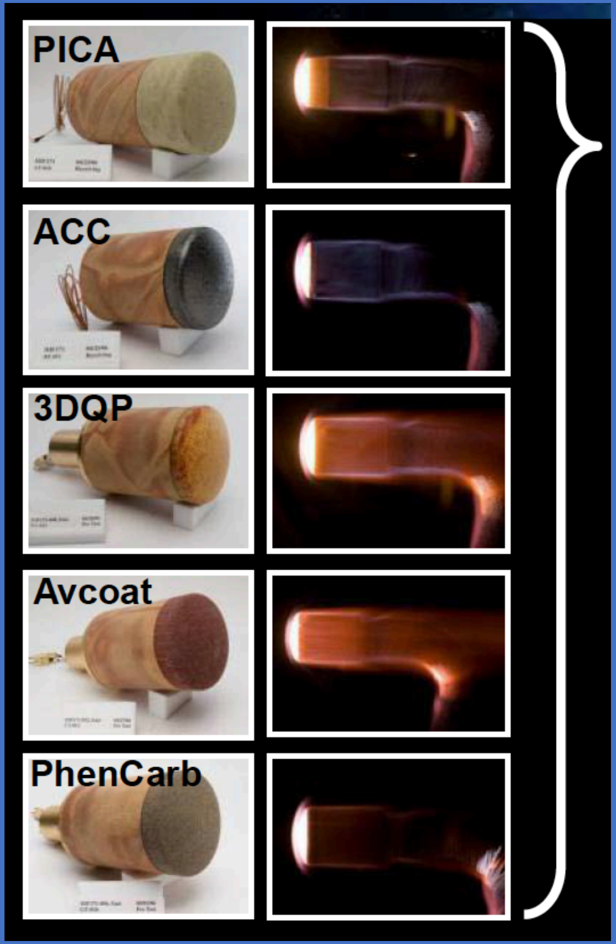
Pathfinder (2.65m) , Stardust (0.83) and Genesis (1.5) (90 's) Smaller " Faster, Better, Cheaper" Missions

- Pathfinder mission with small Sojourner rover,
  - Landed successfully on Mars on July 4, 1997
  - SLA-561V (recovered from Viking era) heat shield
- Stardust sample return capsule at 12.5 km/sec
  - Launched in 1999 returned to Earth Jan. 15, 2006.
  - Phenolic Impregnated Carbon Ablator (PICA)
  - Single piece, seamless heat shield
  - Very capable (> 1000 W/cm2 and > 0.5 atm pressure)
  - Low density (0.25 g/cc) ~ SLA561-V density but capable of much higher entry
- Genesis
  - Launched in 2001, returned in 2004 - Parachute failed
  - PICA manufacturing could not be scaled up in time
  - Advanced Carbon-Carbon + Low density carbon insulation
  - Seamless
  - Forebody penetration


Orion or MPCV or CEV or Artemis (5.0 m) Scaled Apollo CEV TPS Advanced Development Project (2005 – 2008)

Competitive materials R&D multiple materials &systems



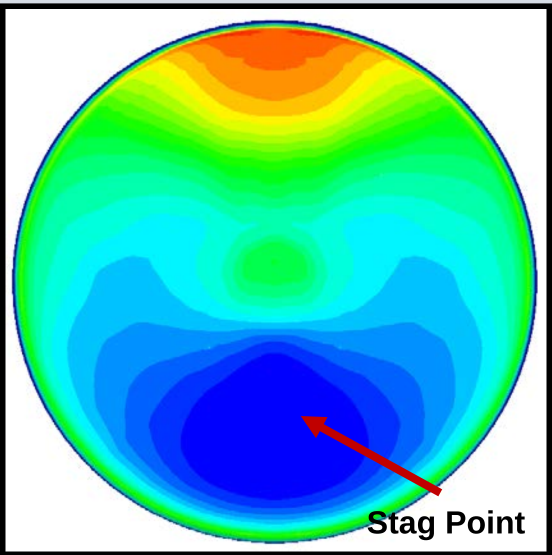
DDT & E of PICA and Avcoat Avcoat Down-selected for Orion

Avcoat Selected for Orion

PICA: Adopted by MSL & SpaceX Dragon

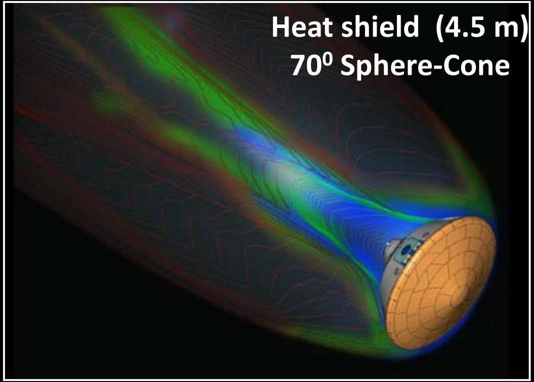
Mars Science Laboratory (MSL) (2005 – 2011)

4.5m dia. – Heat flux - Designed ~ 300 W/cm^2 ; Flight ~ 100 W/cm^2



Heatshield Aerothermodynamics Requirements in 2007 at Max. Heat Flux Location	
Requirement	Value
Max. q_w (W/cm^2)	272
Max. τ_w (Pa)	639
Max. p_w (atm)	0.280
Max. Q_w (J/cm^2)	7588

- Mars Science Laboratory – Largest heat shield to Mars - (Launch Sept ’09)



- (2005 – 2007): Mass “grew”, geometry changed, velocities increased
- Flow on the leeward side predicted to be turbulent
- Conditions were no longer moderate (~2.5x previous Mars missions), especially shear

Orion SLA-561V testing (2007) revealed failure mode - wedge configuration testing at MSL relevant conditions

Courtesy of Robin Beck and Helen Hwang

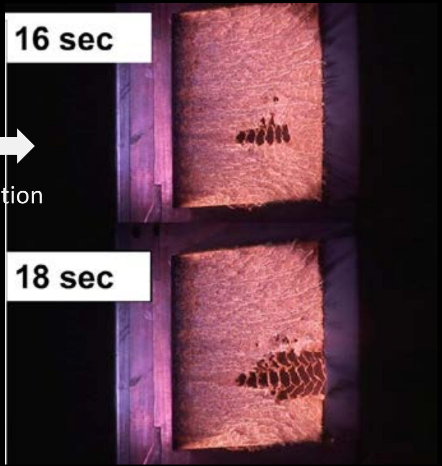
Mars Science Laboratory (MSL)
Switched from SLA-561V to Tiled PICA in 2008

- SLA-561V was an option for Orion (LEO)
- Failure of SLA-561V was reported by Orion to MSL in 2007
- MSL performed further testing and observed failure behavior. Reasons not fully understood

PICA tiles with RTV gap-filler

Wedge Tests

SLA Failed – Wedge Under Moderate Conditions



Flow direction

SLA Failed - Swept Cylinder (June 2007) in 4 sec under Moderate Conditions

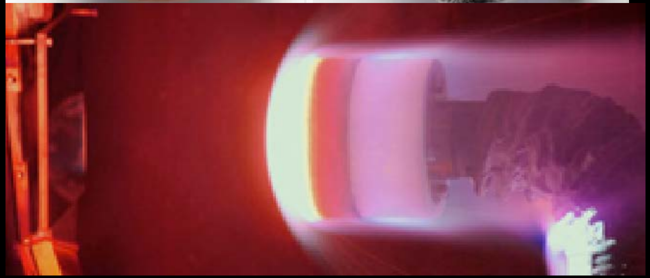
Flow direction

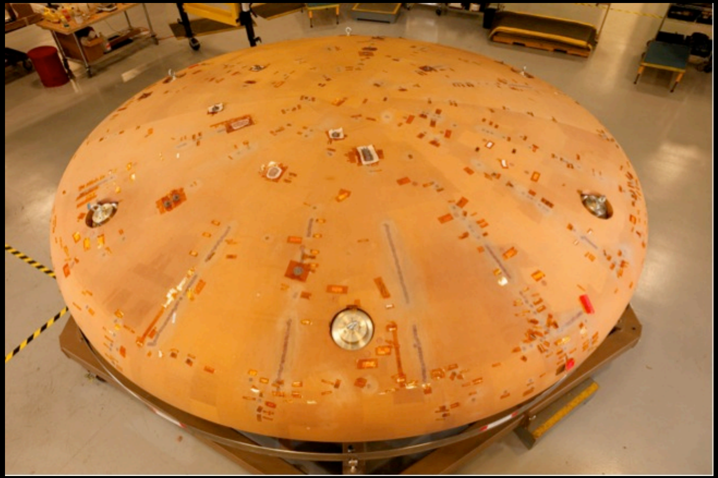
PICA Swept Cylinder well behaved

4.5-m diameter tiled ablative heatshield
(with in-depth instrumentation!)

Launched on December 2011 – Successfully Delivered Curiosity on August 6, 2012,

Back to Orion (2009- 2014)
EFT-1 Flight Test

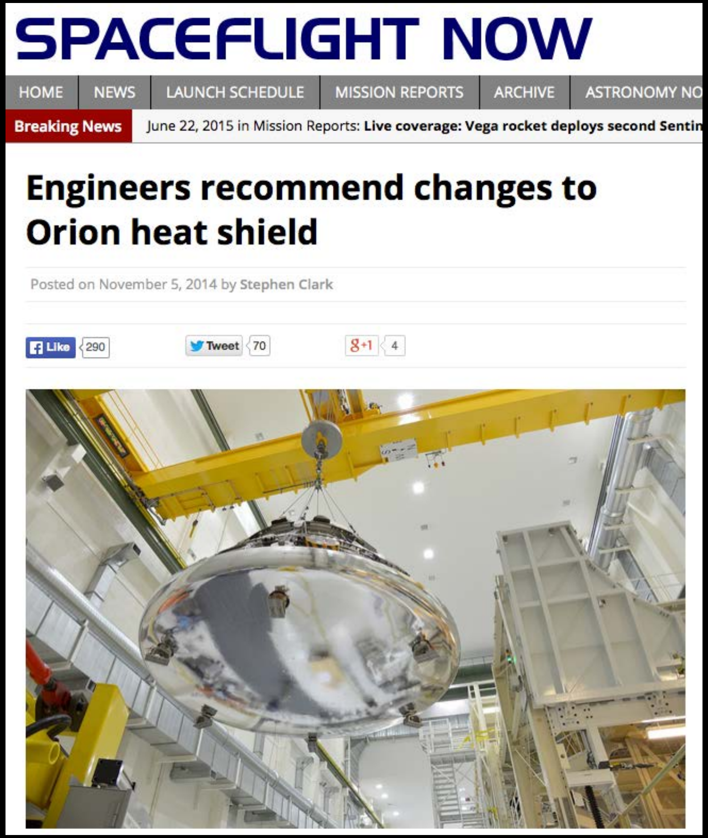




- The largest ablative Heat Shield ever made
- Avcoat™ 5026-39 HC/G (Honeycomb-Gunned)
  - Epoxy novolac resin in a fiberglass honeycomb matrix
- > 300,000 Avcoat™ cells
- 5 meter (16.5 ft) diameter
- 1,800 kg (4,000 lb) including carrier structure
  - ~450 kg (1,000 lb) of Avcoat

Courtesy of Jeremy Vander Kam

Post EFT1 Flight Test – Changed to Artemis Heat Shield (2015)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Breaking News June 22, 2015 in Mission Reports: **Live coverage: Vega rocket deploys second Sentin**

Engineers recommend changes to Orion heat shield

Posted on November 5, 2014 by Stephen Clark

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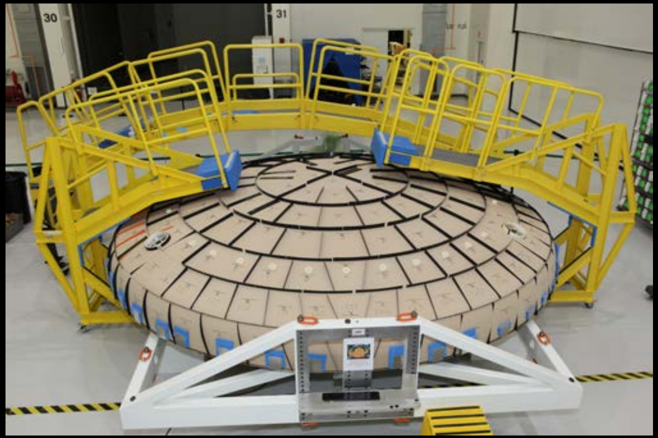
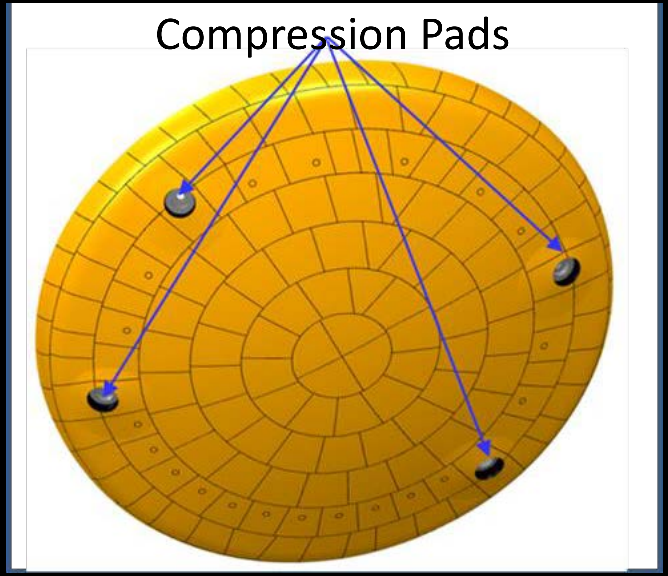
- **Molded blocks** instead of honeycomb
  - Same ablator (Avcoat™ 5026-39)
  - RTV seams tested and verified
  - **~ 300 Avcoat™ blocks** bonded to the carrier structure
    - Compared to 300,000 cells for Honeycomb system
- **Compression Pad** (6 => 4)
  - 3-D woven Quartz / Cyanate Ester instead of Carbon Phenolic shingles
- Improved production and schedule
- Improved manufacturing operations and design integration.
- Improved heat shield thermo-structural capability
- Reduced cost for the EM1 flight test.





Ablative TPS for Future Missions (2020 - 2030)

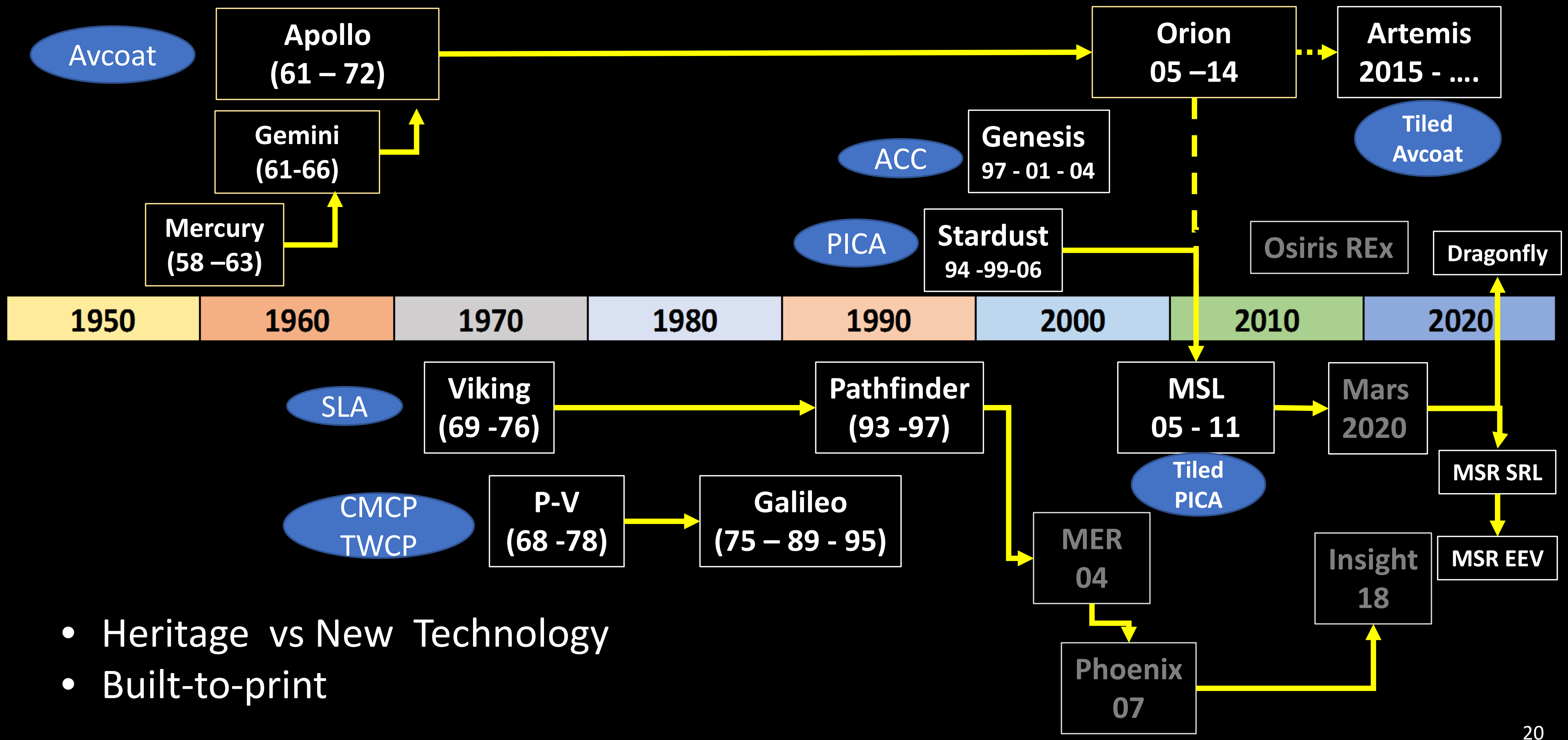
PICA:

- Dragonfly to Titan (2026 Launch) – Plans to use Tiled PICA
- Mars Surface Retrieval Lander – Plans to use Tiled PICA
- Mars Sample Return Earth Entry Vehicle
  - Tiled PICA for the back shell
  - Single Piece PICA (1.3 m) alternate to 3-D Woven

- SLA
  - Mars missions, or on back shell (Dragonfly, MSR SRL)

- 3-D Woven (Heat shield for Extreme Entry Environment Technology - HEEET)
  - Mature at TRL 6 and ready for mission infusion
  - Ice Giant, Venus, Saturn and higher speed Sample Return Missions

History of Ablators – Summary and Observations



- Heritage vs New Technology
- Built-to-print

Concluding Remarks

Ablative TPS enabled:

- Safe return of Astronauts from Moon
- Scientific in situ exploration of solar system bodies and bring samples back.

Lessons from the 7 decades (1950 – 2020):

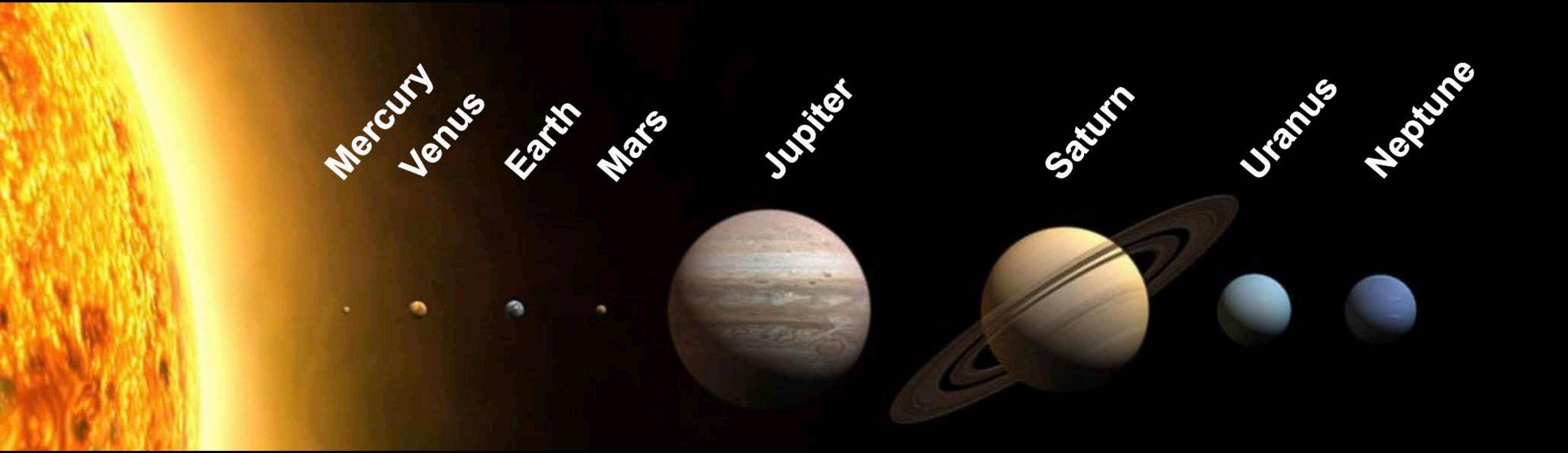
1. Failure is not an option for ablative TPS – Assured design through verification.
   - We have come close but no mission has failed due to ablative TPS
2. System aspects are more important than TPS mass or performance (Apollo, Orion, MSL)
3. Heritage argument has led to problems (MSL and Orion).
4. Recovery from atrophy can take substantial resources and time, and re-certification.
5. Development of new ablative system can be equally or more challenging but needed.

Acknowledgements

I sincerely wish to thank my colleagues at NASA, Industry, Academia and else where, too many to name here, for teaching, mentoring and learning with me over the years.

My colleagues at NASA Ames are very special and my gratitude to all of them.

Thank you for the privilege of your time



Q & A