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Enabling In-situ Science:
Engineering of the Thermal Protection System for future Venus Entry Missions

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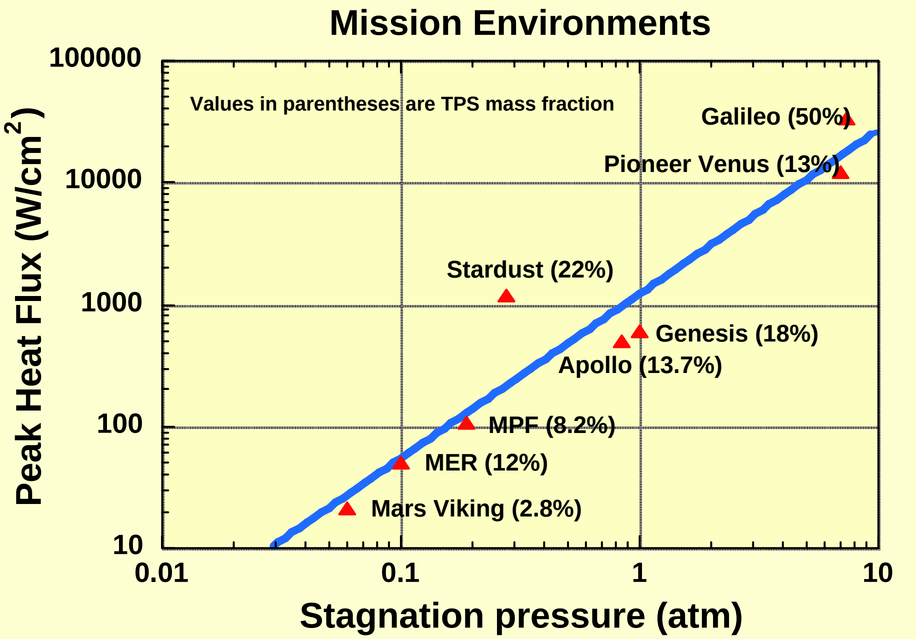
Outline

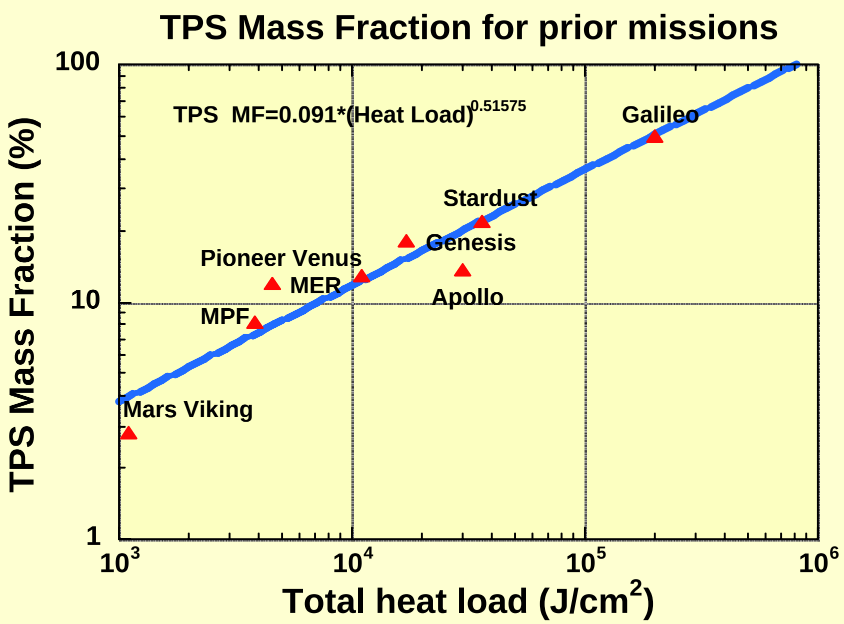
- Motivation and Background
- Venus In-Situ Science and Mission Architectures
- Entry Environment
- Thermal Protection System (TPS)
- Concluding Remarks

Motivation and Background

- **Should we worry about Thermal Protection System (TPS) for Venus?**

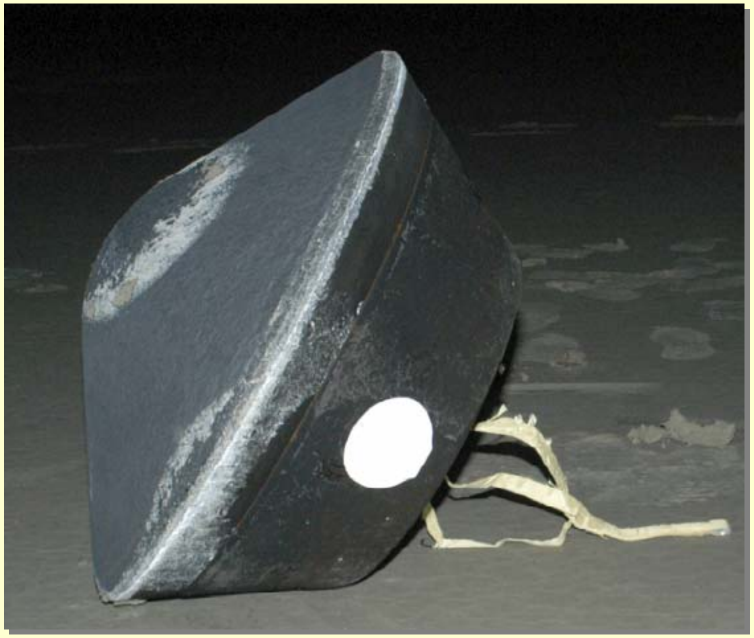
- **NASA entry probes have successfully survived entry environments ranging from the very mild (Mars Viking ~25 W/cm² and 0.05 atm) to the extreme (Galileo ~30,000 W/cm² and 7 atm)**
  - Do we have a TPS solution in hand for Venus today?
  - What are the challenges? What is the current state of TPS technology for Venus?

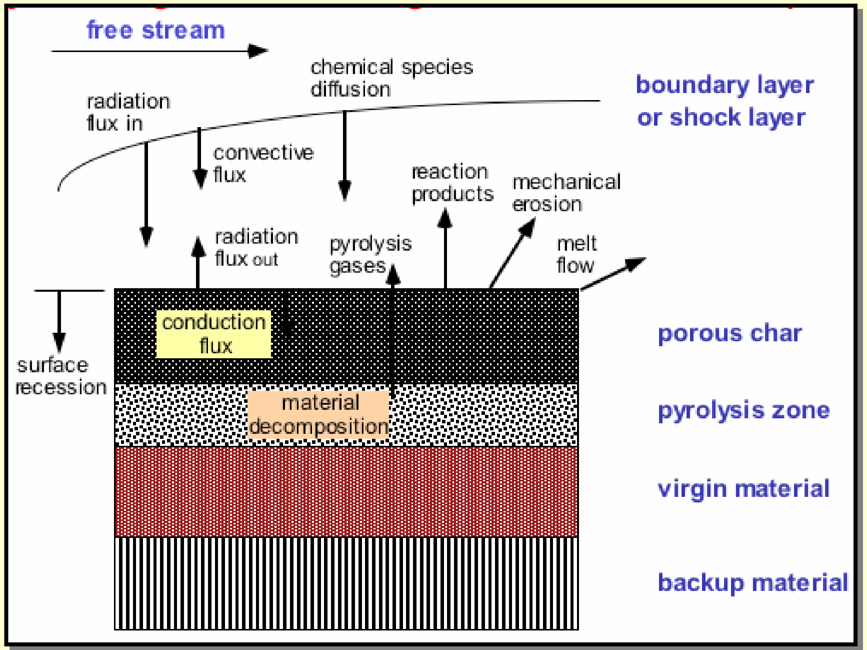




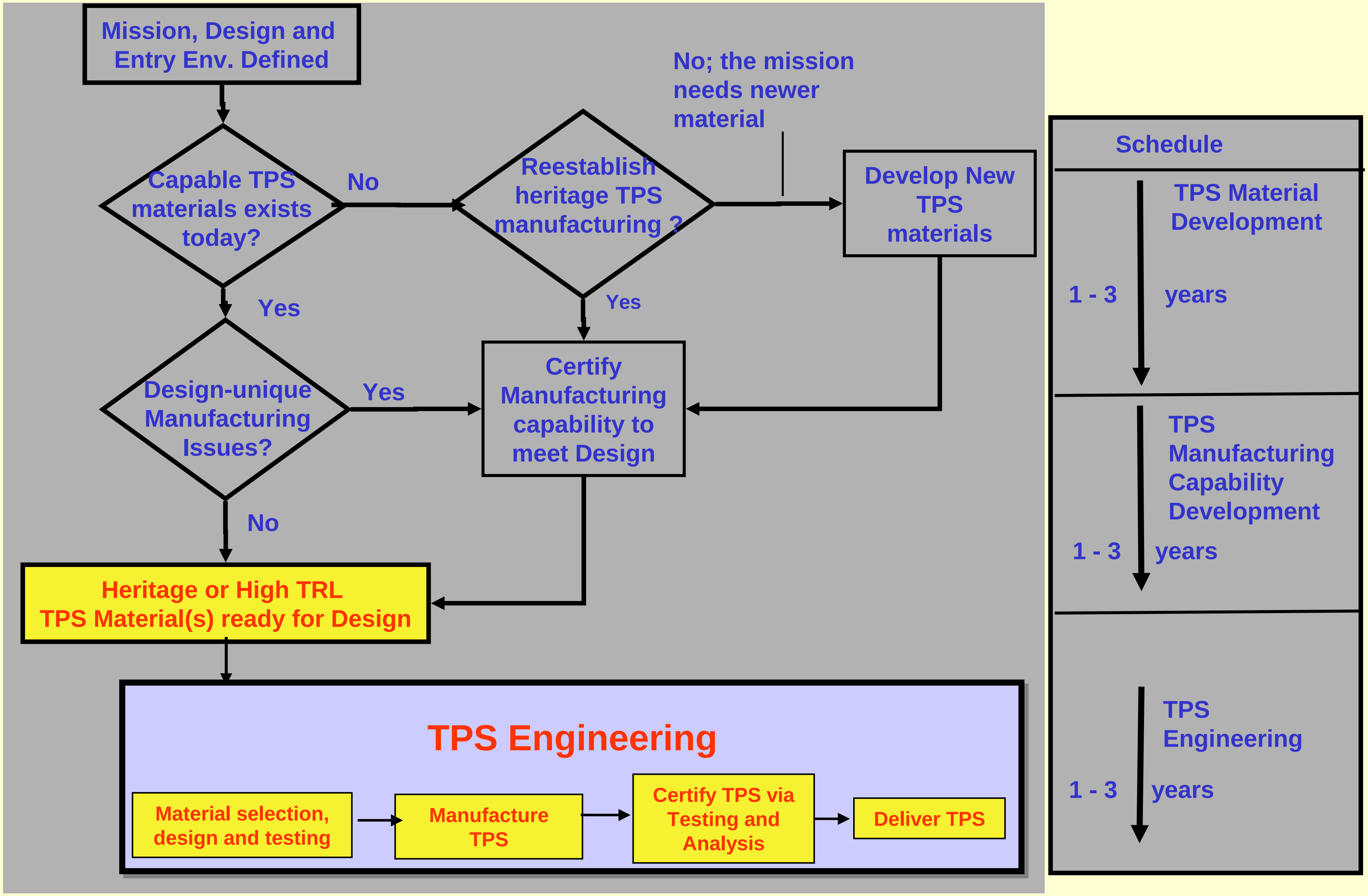
Thermal Protection System (TPS)

- **The TPS for any entry probe is a suite of materials**
  - Materials are selected based on Peak heat flux, pressure, shear, etc.,
  - TPS thickness (mass) is determined by total integrated heat load
- **Reusable TPS vs. Ablators**
- **The science and engineering of TPS requires a multidisciplinary expertise**
  - aerothermodynamics, chemistry, materials science, structures, design, manufacturing, specialized testing, quality assurance, etc.





TPS Development and Engineering Timeline



Engineering of TPS

Engineering is

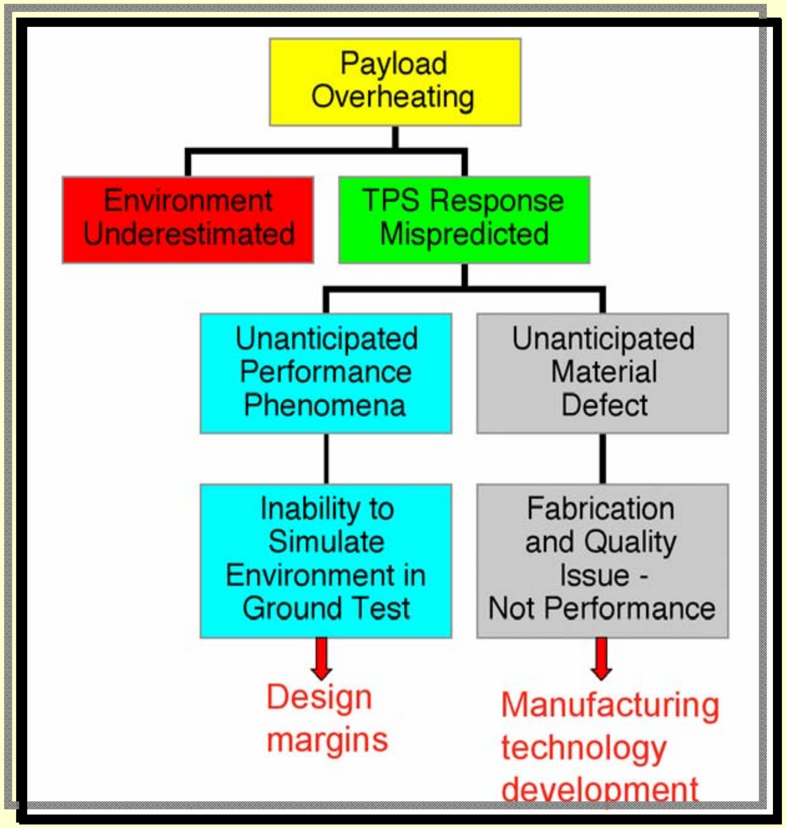
- Designing and building a system to known and and unknown risks; designing to perform the function successfully without unduly impacting other systems

♦ Engineering of the TPS

- Single string sub-system
  - No back-up, hence robust
  - Robust, yet efficient
    - TPS mass is directly tradable with science mass
    - Mass, risk and performance are tradable

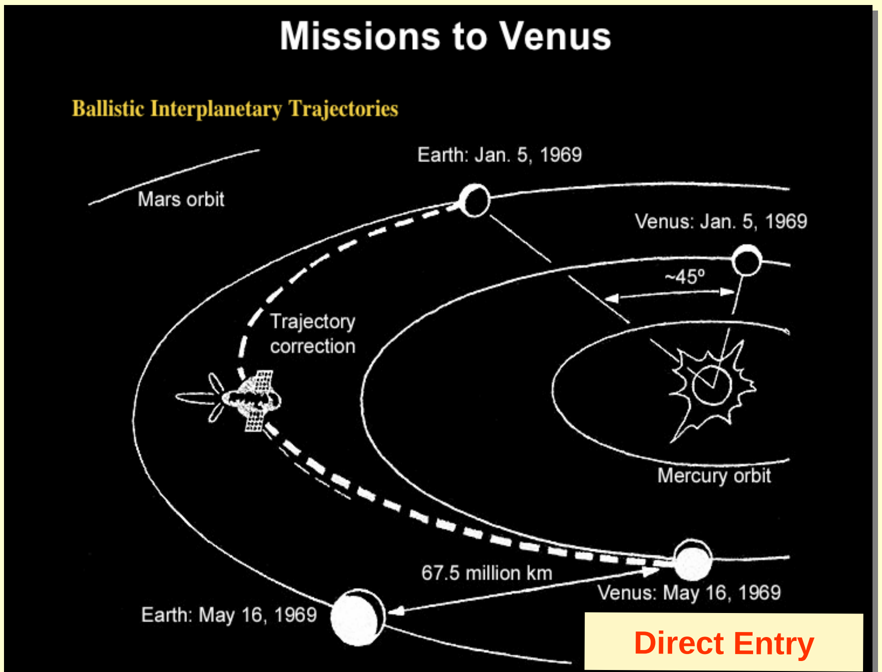
♦ TPS Credibility is achieved via

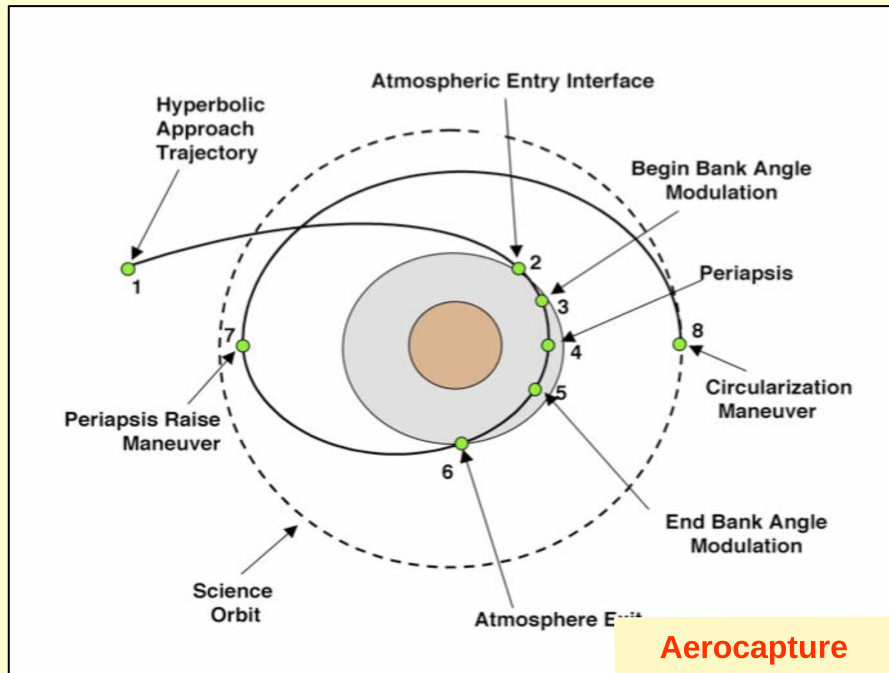
- Use of best practices in
  - Design, Analysis and Testing
  - Hardware Selection - heritage vs. new
    - Comprehensive knowledge on new TPS
    - Not over-extending heritage characteristics
- Verification and validation of the design
  - via qualification tests and analysis



Venus Entry: In-situ Science and Mission Architecture

- **Venus Science: In-situ Measurement for Atmospheric and Surface Science**
  - Mission Architecture => Entry Probe Design (Size, Mass, trajectory) => Entry Heating Environment
- **Architectures:**
  - Direct Entry (Pioneer Venus and Venera)
  - Aerocapture & Entry from Orbit
    - Capture into orbit via a single pass through the planetary atmosphere

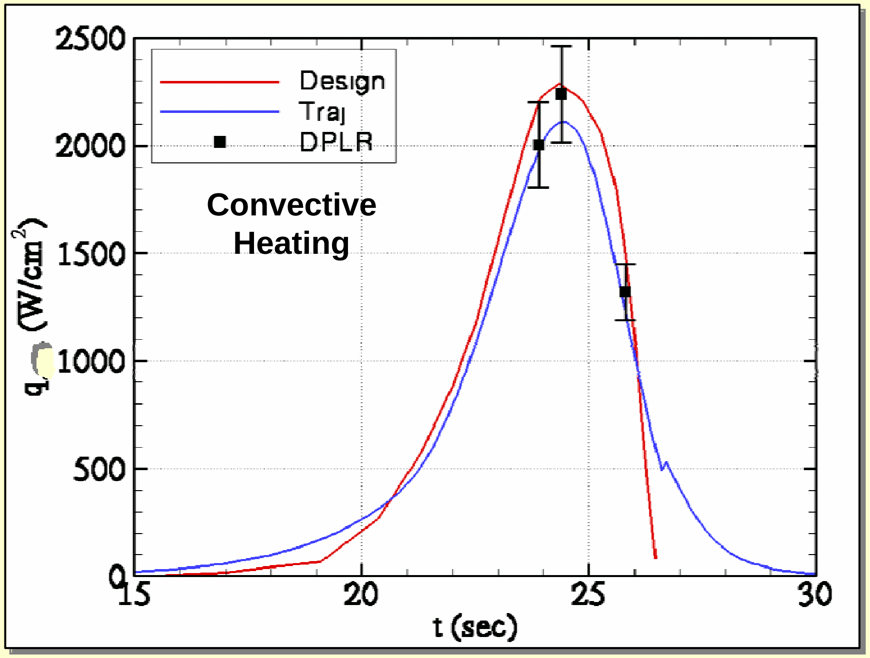


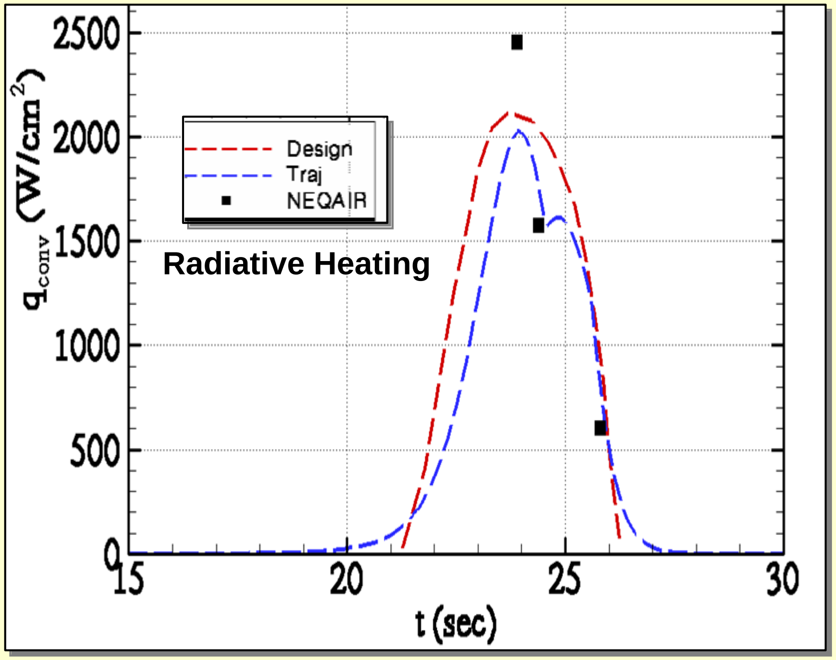


Venus Direct Entry Heating Environment

- **Pioneer Venus Large Probe**
  - Comparison of entry environment prediction with Design Data for P-V Missions
  - Current high fidelity CFD and radiation analysis tools can reproduce heritage design data reasonably well
  - Heating is due to convective heating and shock layer radiation (46%) heating
  - Direct entry has relatively short flight time and hence smaller heat load

Pioneer Venus Large Probe
Comparison to Design Data

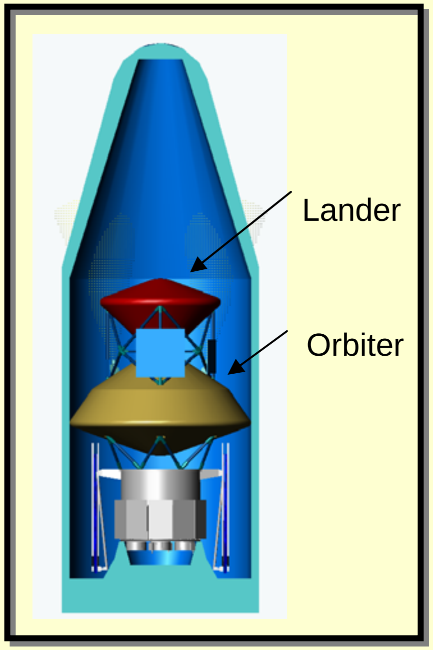




Venus Entry Environment Comparisons

	Direct (P-V) Class			Aerocapture		From Orbit	
	Large	Small	Large	Large	Small	Large	Small
Inertial Entry Angle	γ = -32	γ = -68	γ = -8.5	γ = -8.25	γ = -8.25	γ = -6.0	γ = -6.0
Heat flux, W/cm^2	4500	7200	680	500	600	240	287
Heat load, J/cm^2	12600	12000	25600	39000	48000	16700	22000
G'loads	285	489	22	8	8	9.75	9.75
Pressure, atm	10	18	0.79	0.3	0.3	0.36	0.36
% Radiative	46.0%	34.0%	14.0%	8.0%	4.0%	6.0%	1.5%
Time of flight, s	37	28	227	2783	2785	335	335

- **The comparison study (shown above) uses P-V probes**
  - P-V large (1.42 m) and north (0.762 m) probes
  - Steep entry angle vs shallow entry angle impacts heatshield maerial selection and size
  - Aerocapture assumes a lifting entry to an orbit with a 1000 km apoapsis
  - Orbital entries are from a circular orbit @ 8.6 km/s
- **In-Space Propulsion Technology Program performed system studies for the Venus aerocapture mission**
  - Used a 70 deg. Sphere cone shape at 2.65 m diameter
  - Predicted peak heatfluxes were ~ 1200 W/cm^2 with (700 W/cm^2 from shocklayer radiation and 500 W/cm^2 convective)



Recent Developments in Ablative TPS: Relevance Venus Mission

TPS	Flight Qual. or TRL	Potential Limit		Venus Heat Shield			Venus Back Shell	Other Potential Missions
		Heatflux, W/cm2	Pressure, atm	Direct	Aerocap	From Orbit		
PICA	(green) STARDUST	>1000	< 1 atm	(yellow)	(green)	(green)	(gray)	SR, CEV, Mars
ACC	(green) GENESIS	< 2000	> 1 atm	(yellow)	(green)	(green)	(gray)	SR, , CEV, Mars
AQ60	(green) Huygens	~ 250	< 1 atm	(red)	(green)	(green)	(gray)	Mars, Earth
SLA 561 V	(green) Mars	~ 300	< 1 atm	(red)	(green)	(green)	(gray)	Mars, Earth
SLA 561 S	(green) Mars	< 20	< 1 atm	(red)	(red)	(red)	(yellow)	Mars and Venus (from orbit) Backshell
SIRCA	(green) Mars	~ 150	> 1 atm	(red)	(red)	(red)	(yellow)	Mars, Venus BS
Carbon-Phenolic (CMCP) & (TWCP)	(green) Venus, Jupiter	~ 100,000	>> 1 atm	(green)	(green)	(green)	(gray)	MSR, Venus, Jupiter, Saturn, Neptune
Mid-Density Carbon-Phenolic including ARA PhenCarb Family	TRL 4-5	800 - 10000	> 1 atm	(yellow)	(green)	(green)	(gray)	SR, Venus AC, CEV, Mars
SRAM Family	TRL 5-6	~ 300	~ 1 atm	(red)	(red)	(green)	(green)	Mars, Venus BS
Multi-Layer Systems (Carbon/Silica)	TRL 4-6	TBD	TBD	(yellow)	(yellow)	(yellow)	(gray)	Venus AC
AVCOAT	(green) Apollo/Earth Entry	~ 1000	~ 1 atm	(red)	(green)	(green)	(gray)	Venus AC

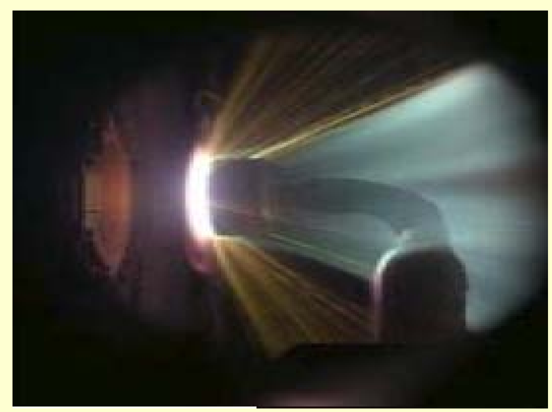
- (green) **Fully capable**
- (red) **Not Capable**
- (yellow) **Potentially Capable Qual. needed**
- (gray) **Capable but heavy**

Candidate Heatshield Materials for Venus Missions

Material	Background	Issues for Venus
PICA	Stardust H/S, 0.875 m diameter single piece low density ablator Carbon fiberform tile impregnated with phenolic resin (36" x 36" x 8" size limit) Qualfied for heat fluxes up to 1600 W/cm2 and pressure < 1 atm	Not applicable to direct entry; applicable to entry from orbit or aerocapture H/S larger than Stardust will require multipiece system - not proven and will require dev't & testing Leverage Crew Exploration Vehicle (CEV) dev't
ACC	Genesis H/S, 1.35 m diameter single piece, 2-layer ablator system Carbon-carbon sheet bonded to carbon Fiberform tiles Qualified for heat fluxes up to 1000 W/cm2 and pressure > 1 atm	Applicability to direct entry unknown; will require extensive testing & analysis Applicable to aerocapture and entry from orbit P-V large probe size H/S may require multipiece Manufacturing unproven; will require dev't and certification testing Leverage CEV (currently a CEV candidate)
Carbon Phenolic	Tape-wrapped and chopped molded constructions Heritage H/S material for P-V and Galileo probes	Only material with heritage and demonstrated capability for direct entry missions (robust) Applicable to aerocapture and entry from orbit (but will exact mass penalty) Baselined for MSR (heritage manufacturing process revived under MSR) Baselined for future proposed missions to Venus, Saturn, Neptune and Jupiter Remaining supply of heritage rayon acquired by Ames and stored for future heritage C/P heatshields

Status and Use of Test Facilities for Venus TPS Development and Engineering

- **Test Facilities**
  - Arc jets provide the best simulation of TPS flight environment, but:
    - Simulation of actual flight conditions $\left(\dot{q}, p, H, \tau\right)$ is rare
    - Most arc jet facilities operate only with air
    - Arc jet designs are tailored to simulate a certain range of conditions (e.g., high pressure, high heat flux vs. low pressure, low-moderate heat flux)
  - Laser facilities offer the opportunity to test at very high heat fluxes not attainable in arc jets (albeit with non-representative pressure, flow, chemistry, etc.)
- **Testing for Venus Direct Entry Conditions**
  - Limitations of the current test facilities
    - ARC and JSC arc jets can simulate low pressures, low-moderate heat fluxes
    - AEDC arc jets can simulate high pressures, high heat fluxes
    - LHMEL (WPAFB) lasers (CO_2, CW, 15 kW,150 kW) potentially useful
- **Proposed Approach to TPS design and verification tests**
  - Testing for Venus Aerocapture and Entry from Orbit
    - Reasonable simulations in ARC and JSC arc jets
  - Testing for Venus Direct Entry
    - AEDC arc jet augmented with laser testing (if necessary)



Leveraging Crew Exploration Vehicle TPS Development for Venus

- **Crew Exploration Vehicle CEV TPS**
  - Advanced Development Project created to address
    - Lunar Capable Heatshield TPS for both LEO and Lunar Return
      - (1000 - 1500) W/cm^2, highly reliable system
    - LEO only back-up
      - (200 W/cm^2), highly reliable system
    - Backshell TPS suite
      - Shuttle derived TPS
  - Extensive risk reduction (manufacturing and scalability) and performance characterization plans (2006 - 2008) underway
  - Flight testing (2008 - 2010)
- **Future Venus missions can leverage current investments from CEV TPS ADP.**
  - (3 - 5) TPS materials will be fully characterized and a high fidelity Thermal Response Model will be in hand
  - Manufacturability and scalability will be comprehensively addressed
    - Up to 5.5 m aeroshell
  - Design tools including radiation modeling will be matured far beyond current state
  - Training ground for young engineers

Concluding Remarks

- **Venus missions <u>do not</u> present significant TPS problems**
  - Re-establishing C-P capability is very nearly completed.
    - Both heritage and alternate to heritage C-P can be manufactured and qualified quickly
  - For aerocapture followed by direct entry, a large suite of TPS materials and options are available to meet mission/design needs
    - Investment in TPS technology for Sample Return Missions have successfully resulted in multiple options
  - Current investment in CEV TPS Technology will have significant payoff to future Venus missions
- **Investment in Venus TPS for direct entry**
  - is a stepping stone for future Saturn, Neptune and Jupiter missions
- **Should you worry about TPS for Venus?**
  - Yes, we should; but we should not lose sleep over it

TPS for Venus is an engineering challenge and not a show-stopper