Selection and Certification of TPS: Constraints and Considerations for Venus Missions

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by

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Introduction, Challenge and Outline

- **TPS:** A mission critical, enabling technology for entry probes and orbital insertion via aerocapture
- **Challenge:**
  - How can TPS technology be **affordably developed and heat shield be certified** for flight despite the fact that we cannot “**test as you fly and fly as you test”.**
  - **Focus is *Venus***
    - *What considerations define TPS selection for missions?*
    - *The challenges for TPS development - “Testing and Design Analysis”*
- **Presentation outline**
  - Mission “pull” for Venus and potential mission architectures
  - Current arc jet test capabilities
  - Filling testing gaps: LHMEL, Solar Tower and DAF (foreign?)
  - Piece-wise certification
  - Candidate TPS (low and mid-density ablators and carbon phenolic)
  - Summary of development/certification for Venus missions

Mission Pull - Venus
Reference - 2002 NRC Decadal Planning

- Atmospheric measurements
  - Composition including trace species and light stable isotopes
  - Accurate determination of noble-gas isotopic abundance
- Descent, surface and ascent meteorological data
- Near IR Descent Images from 10 km to the surface
- Elemental abundances and mineralogy from surface core
- Texturing of surface materials to understand weathering

These science objectives can only be satisfied with entry probes

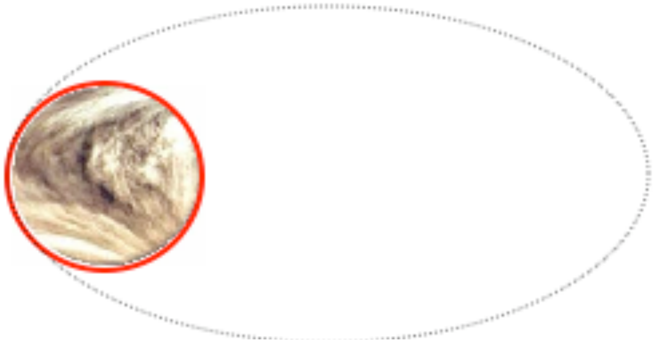
Venus Mission Scenarios

Direct Entry

Descent to surface from interplanetary trajectory

Aerocapture

Orbit insertion via passage through atmosphere from interplanetary trajectory



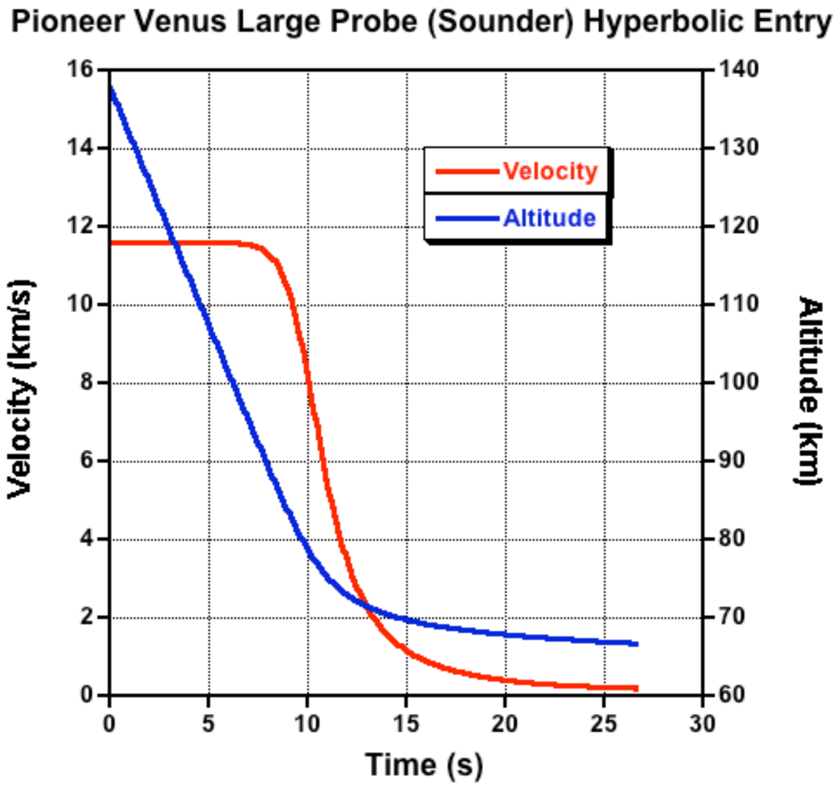
Entry from Orbit

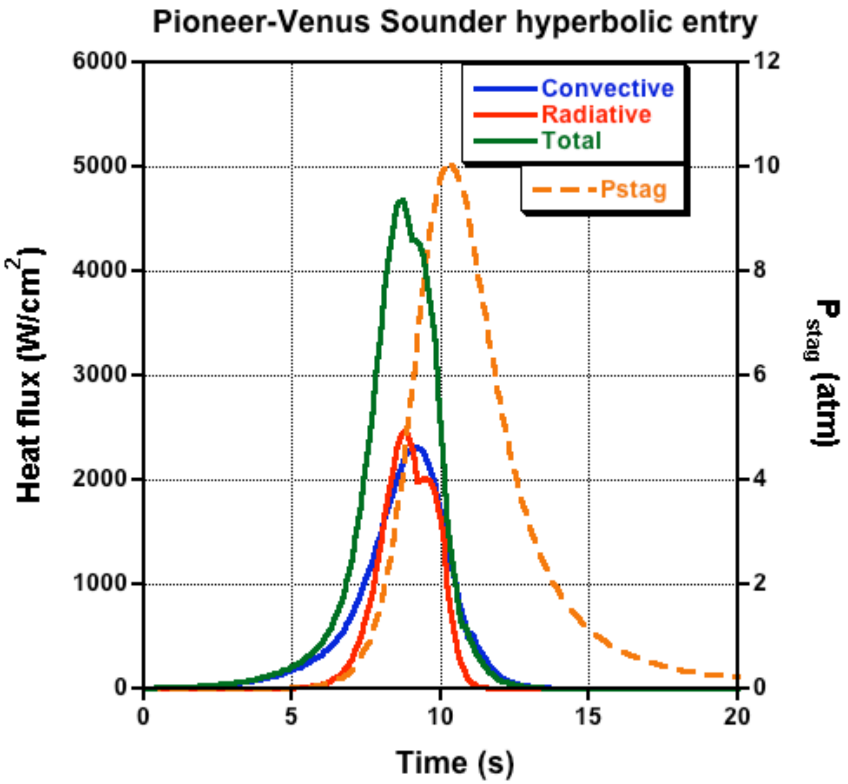
Descent to surface from planetary orbit

	Hyperbolic	Aerocapture	Out-of-orbit
Ve, km/s	11.58	11.18	10.2
qconv, W/cm^2	2319	505	339
qrad, W/cm^2	2459	707	26
pstag, atm	10.1	0.29	0.30
Combined	4685	1212	364
Arc jet simulation?	No	Yes*	Yes*

*Can simulate total heat flux and pressure, but not radiative heating

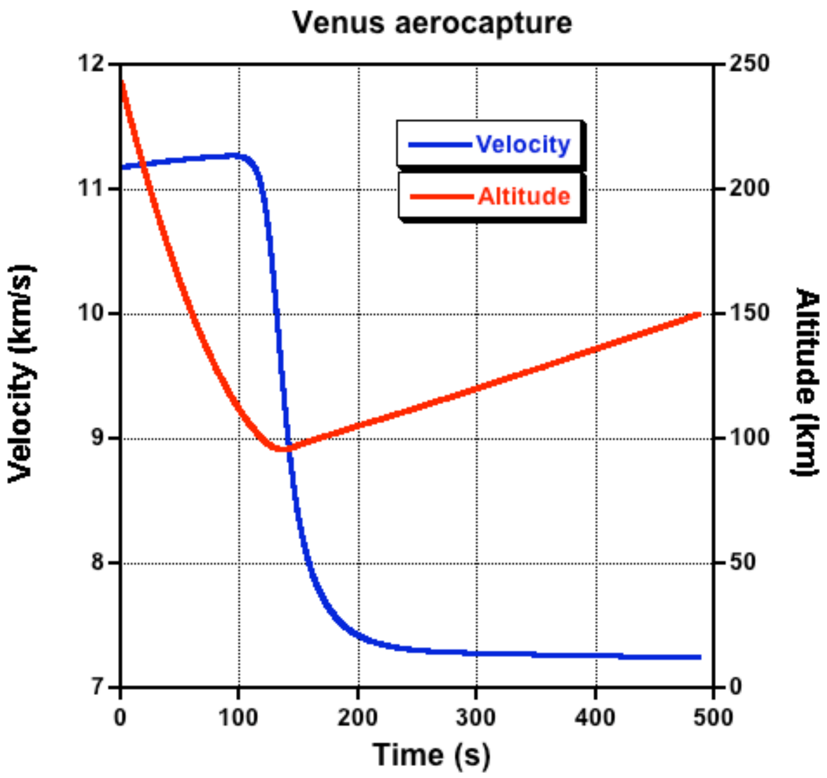
Entry Environment - Hyperbolic P-V Large Probe

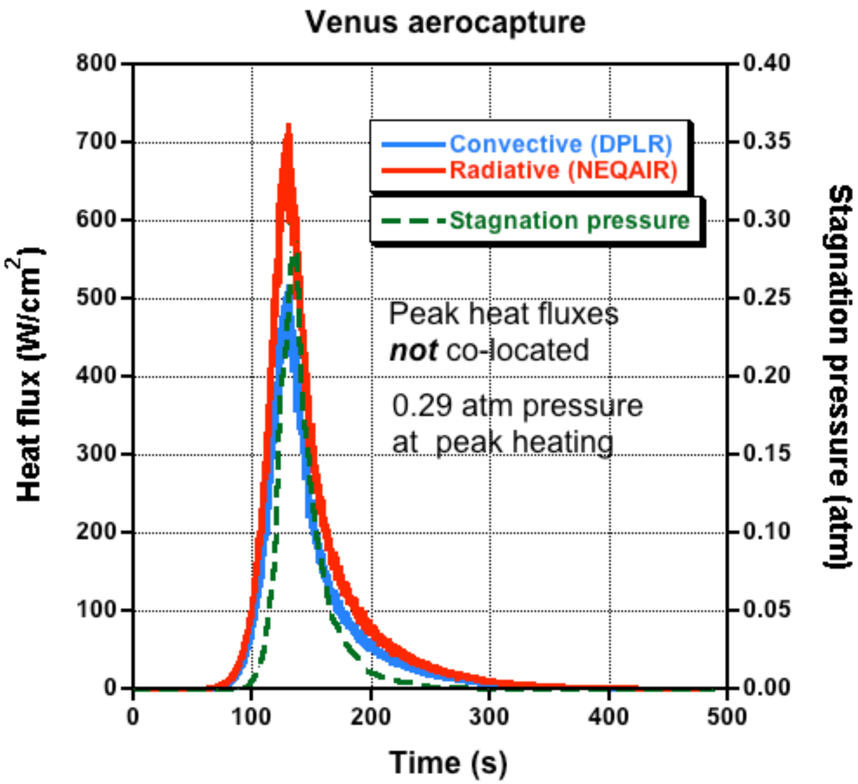

Pioneer Venus Large Probe (Sounder) Hyperbolic Entry


Pioneer-Venus Sounder hyperbolic entry

45 deg blunt cone, 316 kg probe mass, 11.58 km/s relative entry velocity, -31.8 deg relative entry angle

Venus Aerocapture Environments

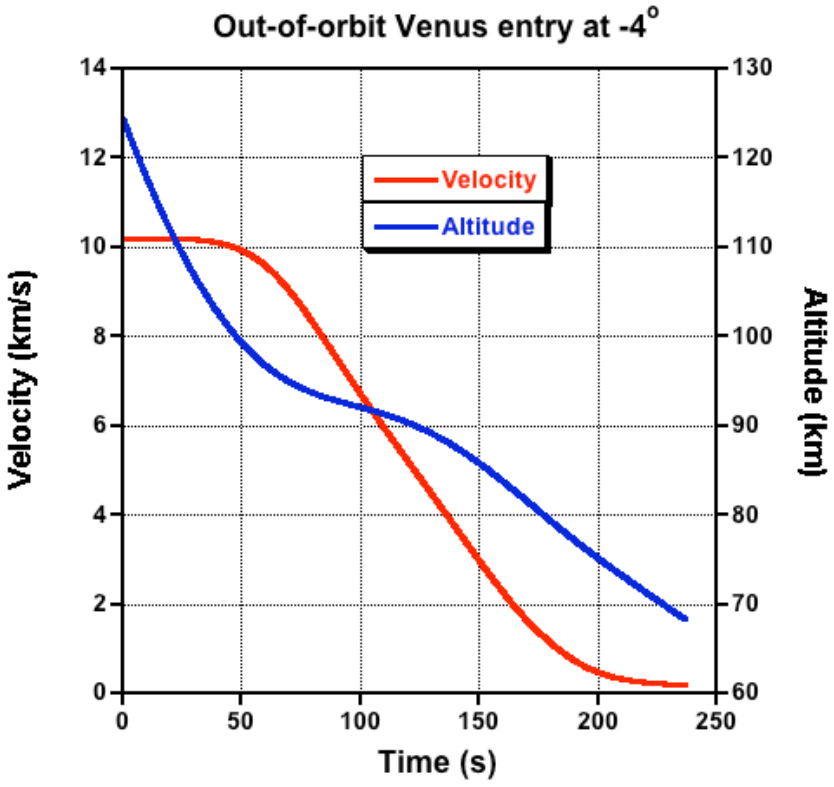


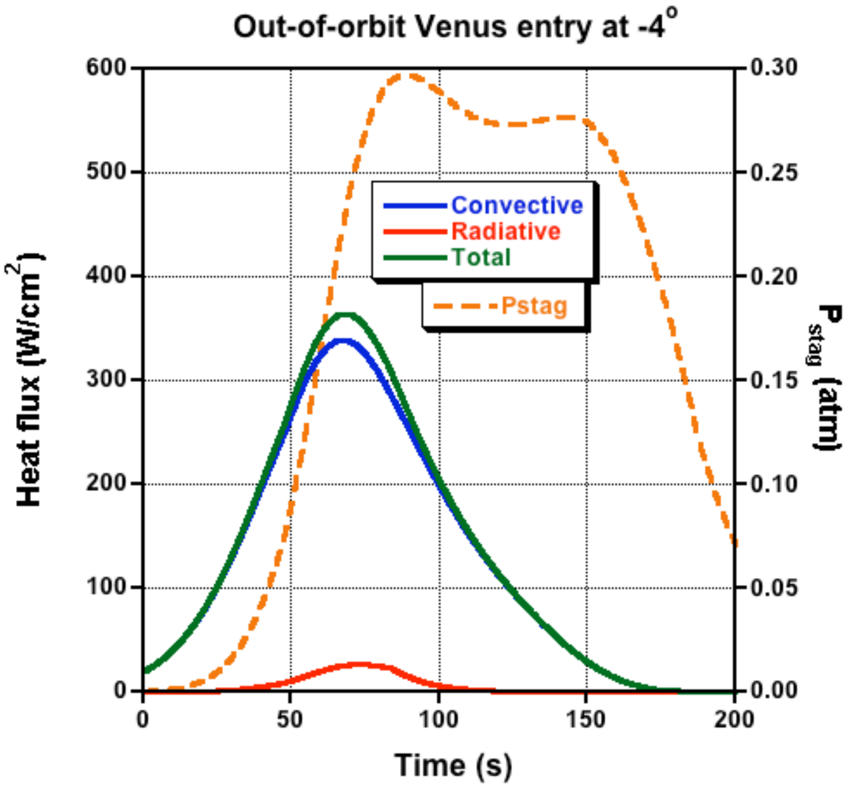


70 deg blunt cone, 2.65 m diameter, Entry mass = 1090 kg, Entry velocity = 11.25 km/s, Atmospheric interface = 150 km, Entry FPA = -6.12°, L/D = 0.25, Exit apoapse altitude = 300 km

Source: ISP Systems Study (2004)

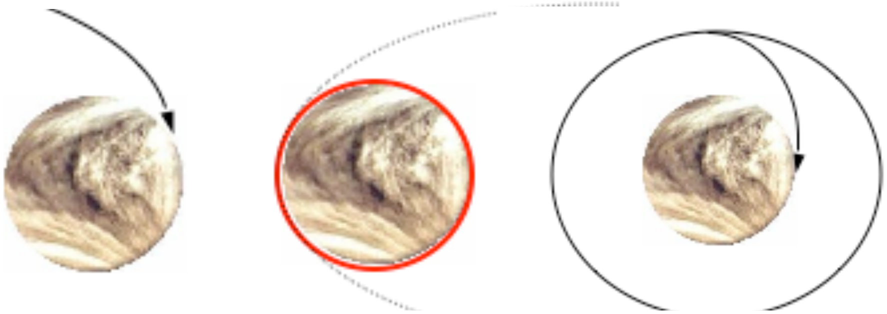
Out of Orbit: P-V Large Probe





45 deg blunt cone, 316 kg probe mass, 10.20 km/s relative entry velocity, -4 deg relative entry angle

Applicability of Some Candidate TPS Materials For Candidate Venus Missions

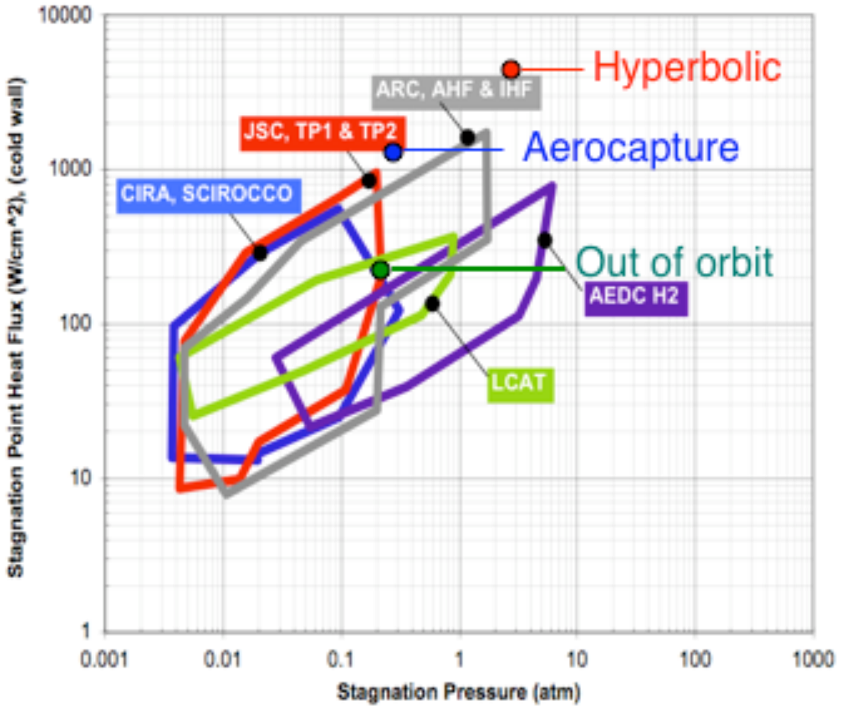


TPS Material	Hyperbolic	Aerocapture	Out-of-orbit	Flight Heritage?
Carbon phenolic	🟩	🟦	🟦	🟩
PICA	🟥	🟩	🟩	🟩
Avcoat	🟥	🟩	🟩	🟩
ACC/insulator	🟨	🟦	🟦	🟩
Densified PICA	🟥	🟩	🟩	🟥
Phencarb	🟥	🟩	🟩	🟥
BPA	🟥	🟨	🟨	🟥

🟩	Applicable
🟦	Applicable, but heavy
🟨	Not enough data
🟥	Not applicable

Current Capabilities - Arc Jet Facilities

4-inch Diameter Iso-Q Test Body



Arc jets provide the best simulation of TPS flight environment, with certain limitations

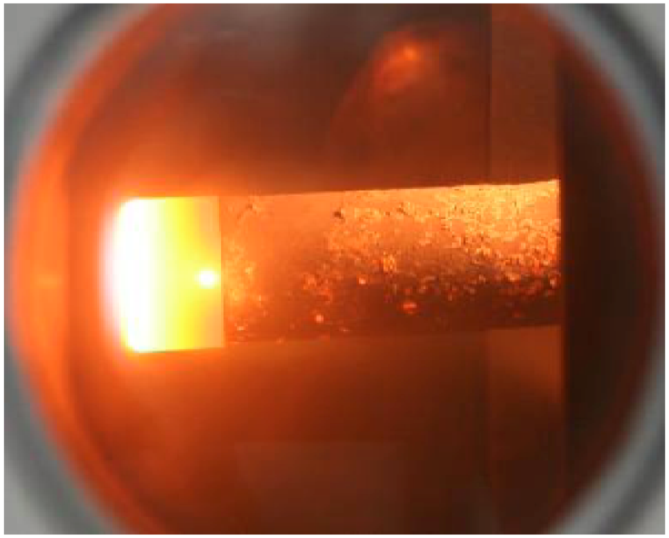
- Cannot simulate all environmental parameters $(\dot{q}, H, p, \tau, \ldots)$ simultaneously
- Most arc jet facilities operate only with air
- Maximum heating on a reasonable size test model is limited to ~2,500 W/cm^2
- ***One cannot match size, density and speed in ground testing, so short of flight testing one cannot achieve the "test as you fly" paradigm***

Venus: Testing Gaps/ Requirements TPS Development Facilities

- **Combined enthalpy, convective heat flux, pressure and shear for hyperbolic entry**
- **Combined radiative and convective heating for aerocapture and hyperbolic entry**
  - Current arc jet facilities would require external sources to augment convective heating
- **Large scale test articles**, to reduce size scaling
  - Requires higher heater power relative to peak heat flux
- **Atmosphere is 95% CO_2, NOT air…**

Non-Air Arc Jet Facilities

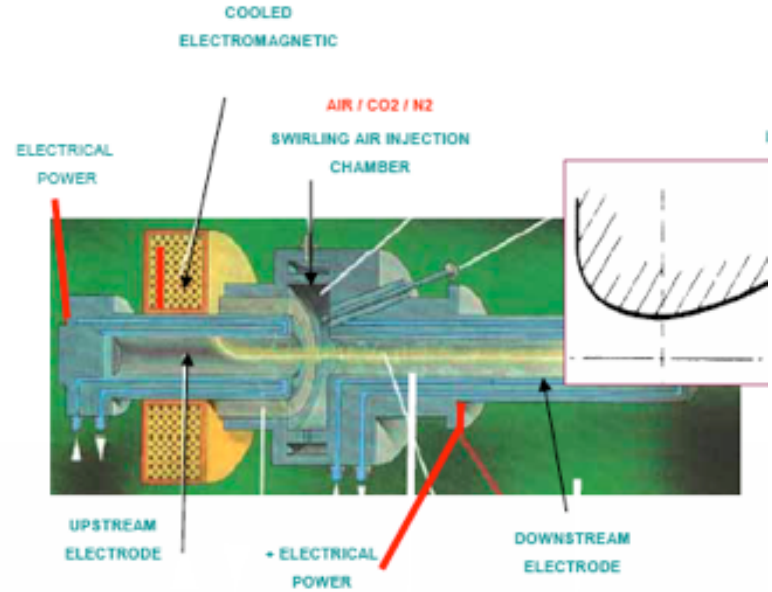
LaRC HyMETS: 400 kW Facility



NASA LaRC Hypersonic Materials Environmental Test System (HyMETS) Facility capable of running on Carbon Dioxide for Venus atmosphere simulation

- Test articles ~1.0 inch diameter
- CO_2
- q_{cw}: ~TBD W/cm^2
- P_{T2}: ~TBD atm
- (Operating envelope definition starting in Aug-Sep)

EADS Simoun 6 MW Facility



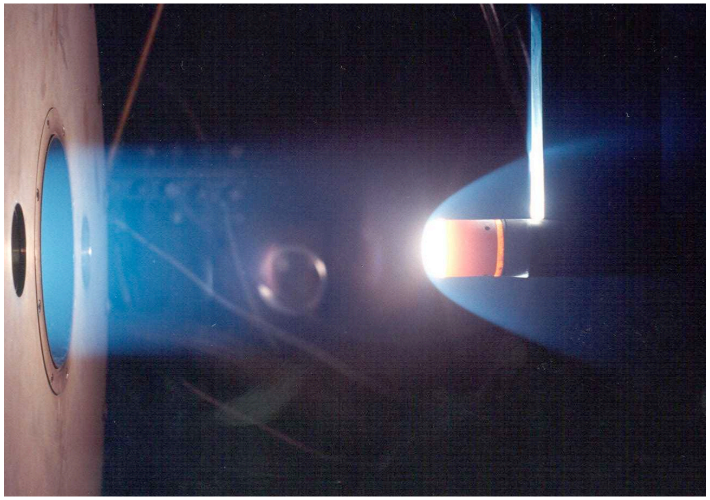
6 MW SIMOUN Facility with a Hüls Type Arc Heater capable of running on Carbon Dioxide for Martian atmosphere simulation, both with and without dust

Stagnation Point Configuration

- Test articles: 50 mm diameter
- CO_2 97% / N_2 3%
- q_{cw}: ~130 W/cm^2 (w/o dust)
- P_{T2}: ~0.10 atm

Non-Air Arc Jet Facilities (concluded)

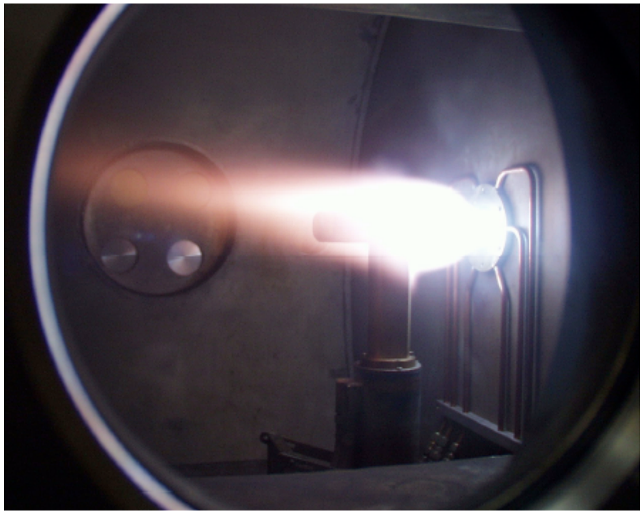
DLR L2K Facility



1.4 MW L2K Facility with a Hüls Type Arc Heater is capable of running on Carbon Dioxide for Martian atmosphere simulation

- Test articles ~50mm diameter (ESA geometry)
- CO_2 97% / N_2 3%
- q_{cw}: ~76 W/cm^2
- P_{T2}: ~0.016 atm
- H_0: ~15.6 MJ/kg

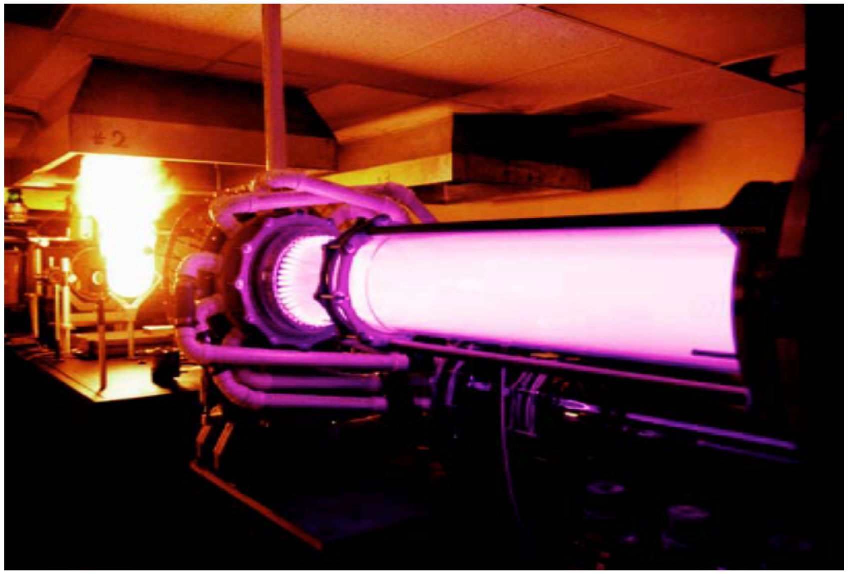
IRS PWK3 Facility



IPG driven (inductively heated) PWK3 Facility capable of running on Carbon Dioxide for Martian atmosphere simulation, both with and without dust

- Test articles ~ ? mm diameter
- CO_2 97% / N_2 3%
- q_{cw}: ~140 W/cm^2 (w/o dust)
- q_{cw}: ~170 W/cm^2 (with dust)
- P_{T2}: ~0.019 atm

Laser Facility - LHMEL



- Non-representative pressure, flow, chemistry..
- Simulates surface temperature and oxygen pressure in a low-flow or subsonic radiating environment Does not simulate boundary layer structure (convective transport)
- Delivered power of 100 kW = maximum heating of ~7,000 W/cm^2 on a reasonable size test model (≈40 mm diameter)

Limitations and value added

Radiation spectra is very different than flight. No simulation of Qdot convective

Boundary layer chemistry is wrong

Thermal response data at high heat fluxes would be of value assuming good comparison at overlap with convective heating data from arc jets using air as test gas

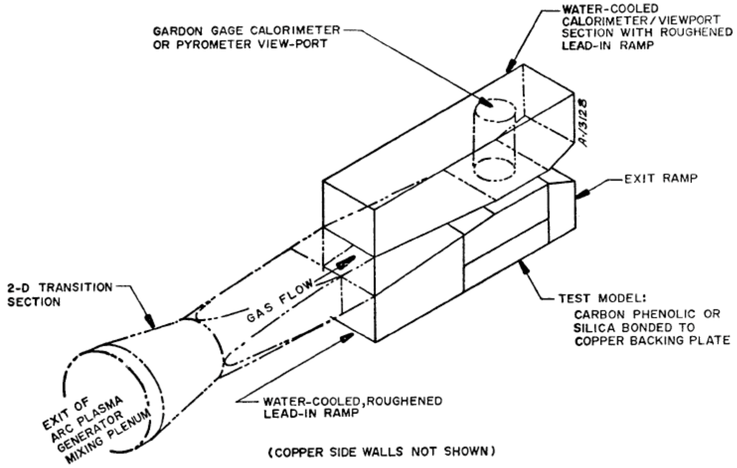
Excellent for determining failure modes, especially spallation as per Galileo

Large model size possible (at correspondingly lower heat flux)

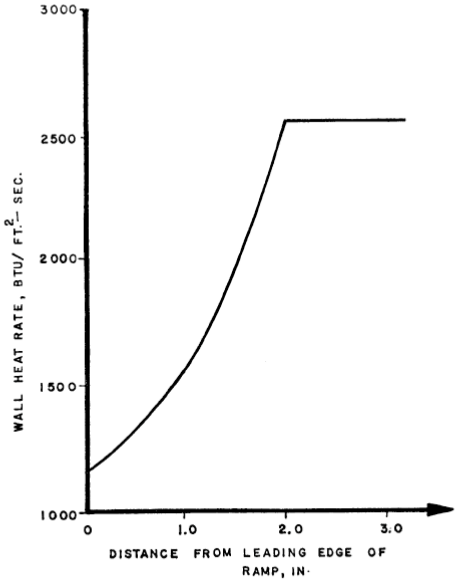
ARC Development Arcjet Facility (DAF) Testing

2-D Nozzle Test Configuration

2-D Test Configuration

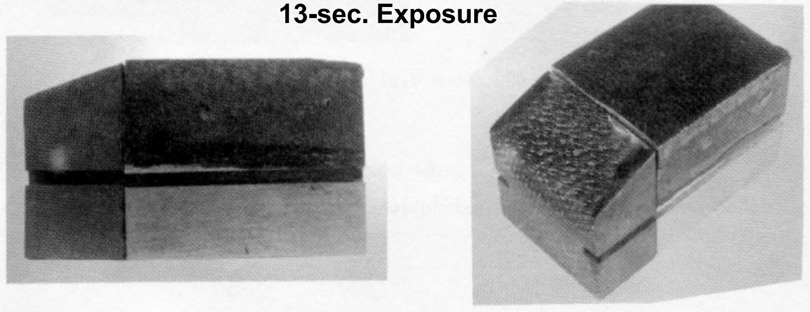


Predicted Heating Distribution on Test Model



Based on previous work done at the Aerotherm 1-MW APG Facility[†], where the test model formed the throat region of a 2-D nozzle with sample nominal dimensions of 1.0 inch wide x 0.95 inch long. Lead-in ramp roughened to promote turbulent flow. 75% H_2 / 25% He (Jupiter nominal) test gas shown as example. Facility can operate on wide variety of test gases including air, nitrogen, argon, carbon dioxide, and hydrogen/helium.

Carbon Phenolic Test Sample after 13-sec. Exposure



[†] Aerotherm TM-76-106, March 1976

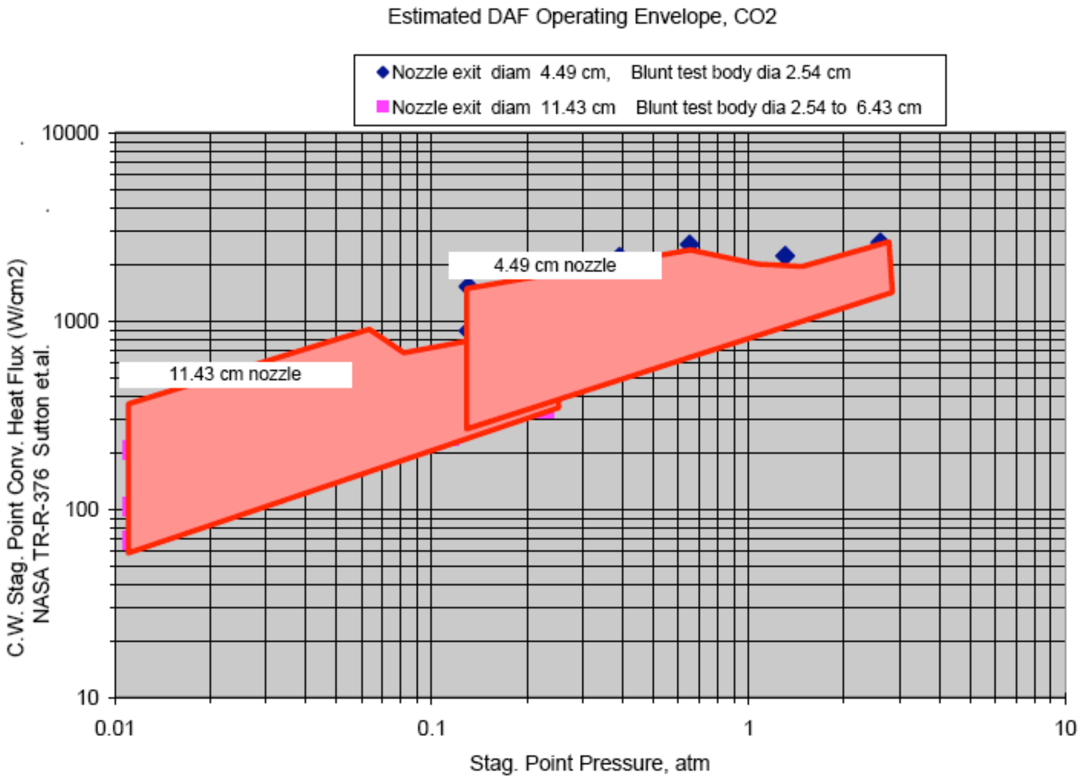
Proposed DAF Testing in CO_2

Stagnation Test Configuration

Performance predictions† for DAF with various conical nozzles, subsonic electrode configuration, 95% CO_2 / 5% N_2 (molar) test gas, and 2.54 cm diameter test model:

Maximum heating rate at:

- Maximum stagnation pressure
  - q_{cw}: ~2,500 W/cm^2
  - P_{T2}: ~2.5 atm
  - $H_{centerline}$: ~30 MJ/kg
- Maximum centerline enthalpy
  - q_{cw}: ~2,500 W/cm^2
  - P_{T2}: ~0.65 atm
  - $H_{centerline}$: ~58 MJ/kg



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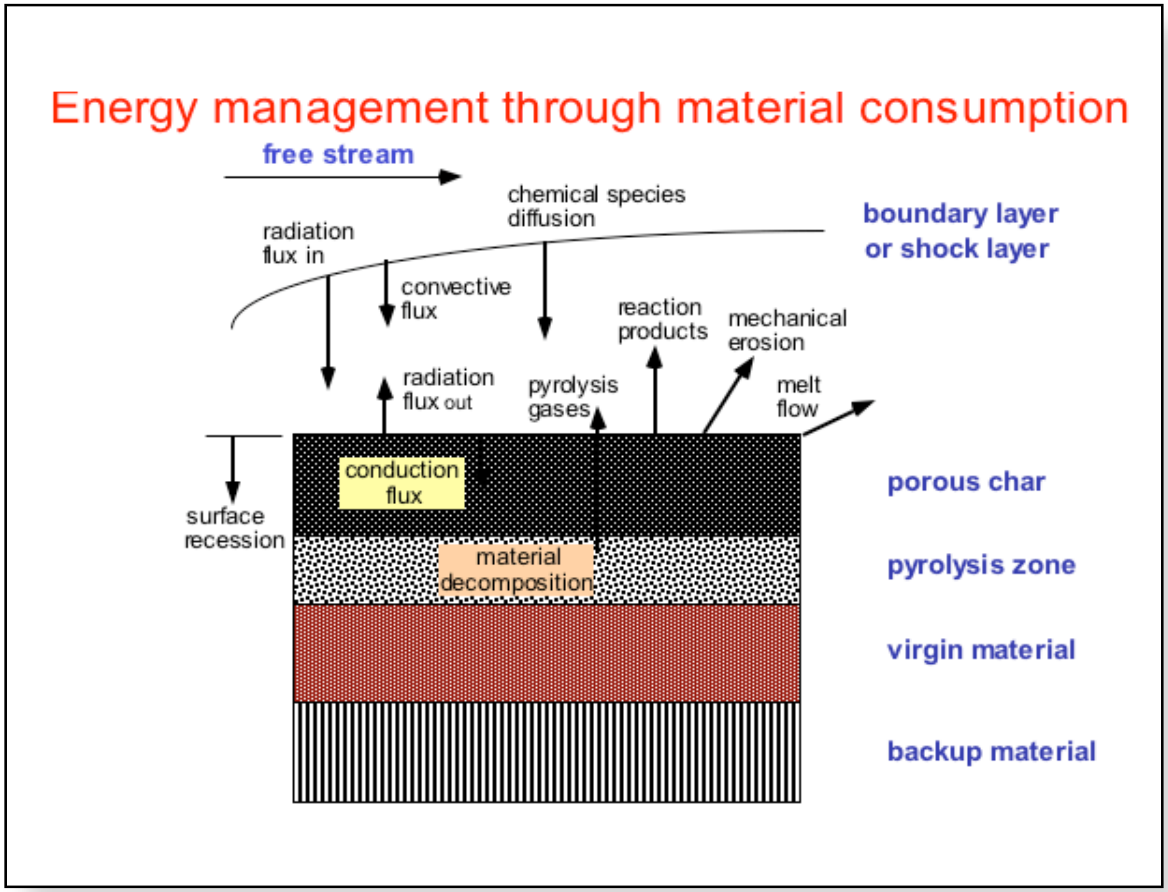
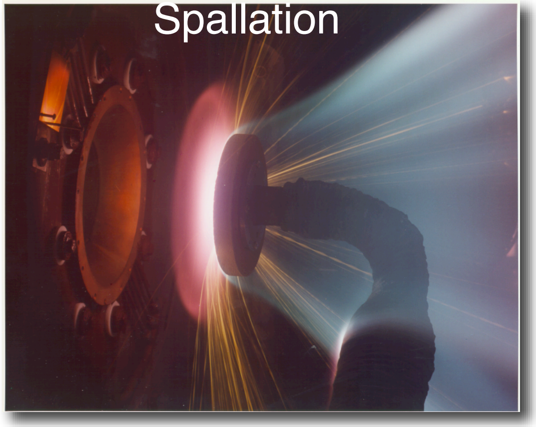
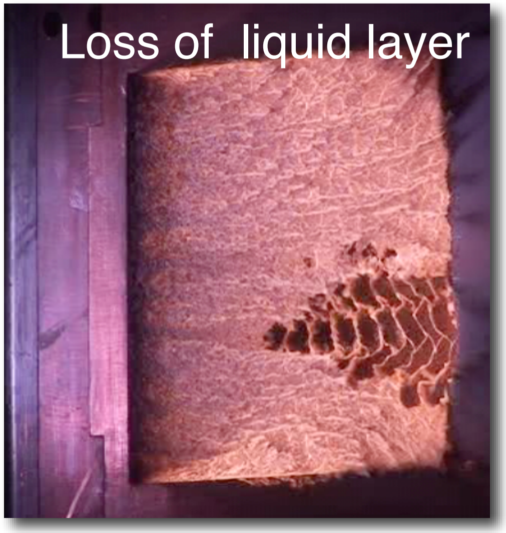
† by John Balboni, NASA/ARC

Complexity of Ablative TPS



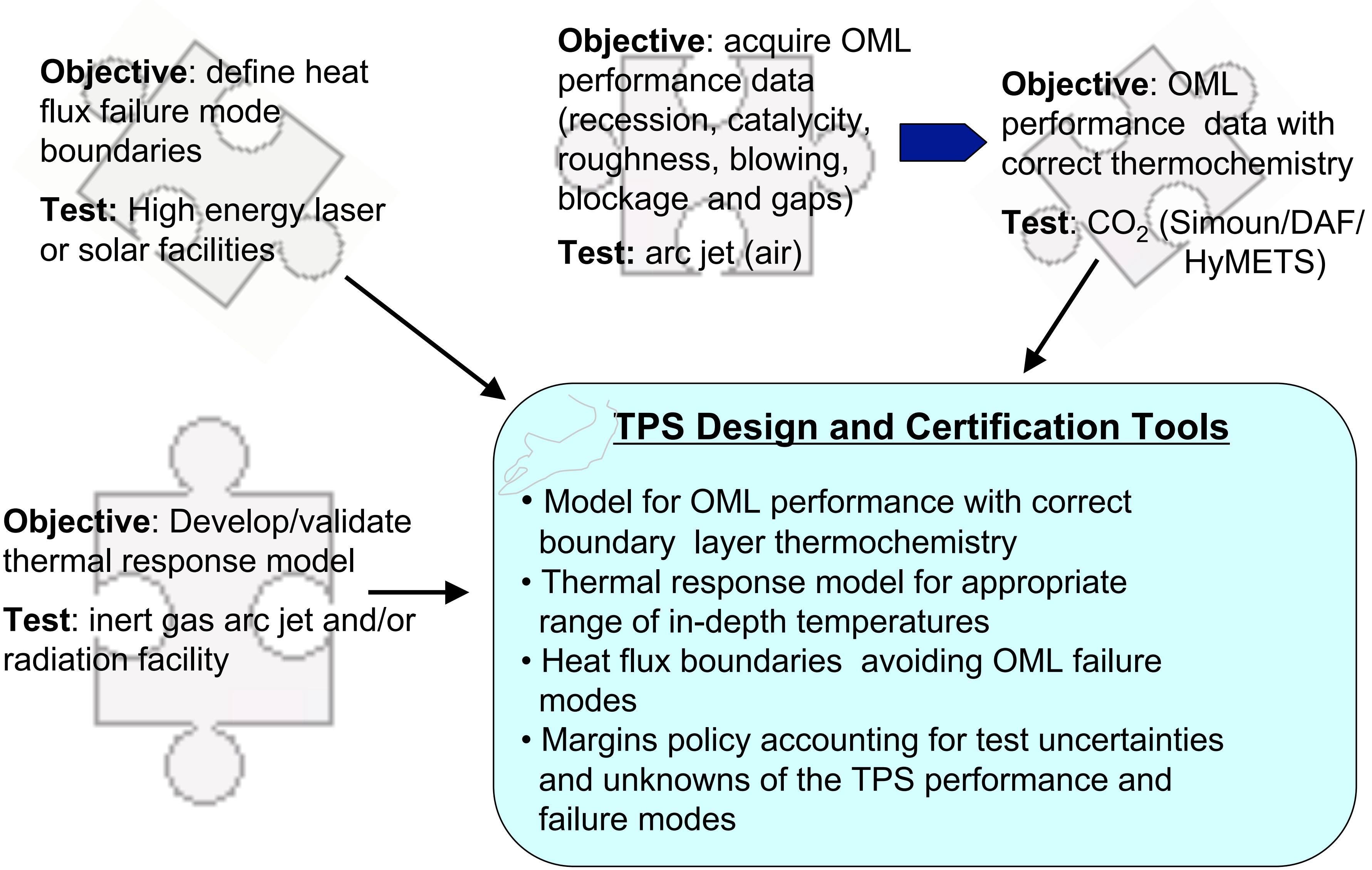
Physics of TPS Performance - Modes


Spallation


Loss of liquid layer

Failure - Modes

TPS Piece-wise Certification



Objective: define heat flux failure mode boundaries

Test: High energy laser or solar facilities

Objective: acquire OML performance data (recession, catalycity, roughness, blowing, blockage and gaps)

Test: arc jet (air)

Objective: OML performance data with correct thermochemistry

Test: CO_2 (Simoun/DAF/HyMETS)

Objective: Develop/validate thermal response model

Test: inert gas arc jet and/or radiation facility

<u>TPS Design and Certification Tools</u>

- Model for OML performance with correct boundary layer thermochemistry
- Thermal response model for appropriate range of in-depth temperatures
- Heat flux boundaries avoiding OML failure modes
- Margins policy accounting for test uncertainties and unknowns of the TPS performance and failure modes

Carbon Phenolic for Venus

- Heritage carbon phenolic (P-V and Galileo) no longer manufactured
  - Very limited supply of heritage CP
  - Current CP employs carbon cloth derived from new rayon source
  - Limited arc jet tests show performance similar to heritage
- Test in high energy laser facility (e.g., LHMEL) to demonstrate capability at max combined heat flux
  - Verify absence of failure modes
- Test in CO_2 arc jet (e.g., DAF) to demonstrate applicability of theoretical thermochemical ablation models to performance in Venus atmosphere
- Validate/update heritage in-depth thermal response models via arc jet tests of instrumented samples at well-defined conditions (e.g., IHF)
- Combine surface ablation and in-depth thermal response models into Venus entry design model for carbon phenolic
- Heat shield design and certification is easier with **heritage** C-P
  - Pioneer-Venus and Galileo experience
  - Robust; applicable for conditions far exceeding any Venus mission and is truly off the shelf.

PICA/Avcoat/ACC for Venus

- PICA is the baseline forebody TPS for Orion's Crew Exploration Vehicle (CEV) and MSL
  - Successfully used as the forebody heatshield on Stardust
- Avcoat 5026-39/HC-G is the alternate forebody TPS for Orion
  - Successfully used on Apollo 40 years ago
- ACC has limited demonstrated performance capability
  - Failure modes not well-established
- The first two materials are being extensively evaluated by the CEV Advanced Development Program via testing, analysis and manufacturing demonstrations
  - An extensive database has been developed for PICA; failure modes are understood (do not exceed 1500 W/cm^2 and 1-1.5 atm); validated design models available
  - A more limited database is being developed for Avcoat to demonstrate that properties and performance are consistent with heritage material
- Attractive for out-of-orbit and/or aerocapture segment of the design
  - Leverage on-going CEV Orion developments for PICA and AVCOAT
  - C-C will require failure mode testing and analysis development

Mid-Density (Low TRL/IRL) TPS Development Challenges

- Available "off-the-shelf" materials applicable to TPS for planetary probes are very limited
- Several mid-density (480-960 kg/m^3) ablative materials are attractive candidates for some planetary missions
  - PhenCarb (ARA), Densified PICA†, mid-density C-P† and BPA (Boeing)
  - More robust than low density materials, i.e., capable of reliable performance at higher heat flux and pressure
  - TPS mass savings in comparison to high density materials, e.g., carbon phenolic
- Qualification and certification of these "new" materials for mission use would require a significant amount of testing, modeling and analysis
  - **Reliability requirements << crewed missions**
  - **Who would sponsor such development?**

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†Modest development being sponsored by NASA's Hypersonics Program

Conclusions/Recommendations

- *Test as you fly and fly as you test* is generally not possible for TPS
- Approach for affordable TPS development and certification for Venus Direct entry and Aerocapture has been outlined
  - Define mission scenarios
  - Evaluate candidate TPS
  - Evaluate arc jet and other testing capabilities
  - Piecewise determination of material properties and failure modes

Certification by combination of testing and analysis

- Recommendations:
  - Near-term Venus missions: Cost-effective and robust TPS solution is *heritage* carbon phenolic
  - Need CO_2 arc jet capability relevant for Venus conditions - complete DAF to support TPS testing for Venus missions
  - Optimal TPS solution for future Venus missions requires a dedicated TPS advanced development program