Outline - Entry Segment

- Entry (Raj Venkatapathy)
  - Historical perspective
  - Classical Venus entry
  - Entry Aerodynamics and Aerothermodynamics
  - Entry Parameters and Mission Design
  - High and Low Ballistic Coefficient Entry System
  - Thermal protection system (TPS)

- Entry System Mission Design Case Studies (Brandon Smith)
  - VITaL – A Decadal Mission Design Study as baseline
  - ADEPT-VITaL (low ballistic coefficient)
  - Mid-density materials (HEEET)

- Summary

Key Questions: what you will learn

- What happens during entry at Venus?
- What entry physics aspects governs the interaction of the atmosphere with the entry system?
- What is an entry system (or aeroshell)?
- How do we design an entry system? From preliminary to detail design?
  - Shape of the entry system?
  - Aerodynamic and entry heating environment?
  - Choosing the TPS?
  - Mass estimation?
- What are recent developments in technology that can enable future science missions?
- Examples

Venera 4: The First Planetary Entry Mission

- Show segments from the You-tube Video

https://www.youtube.com/watch?v=f2XdUT4wocQ

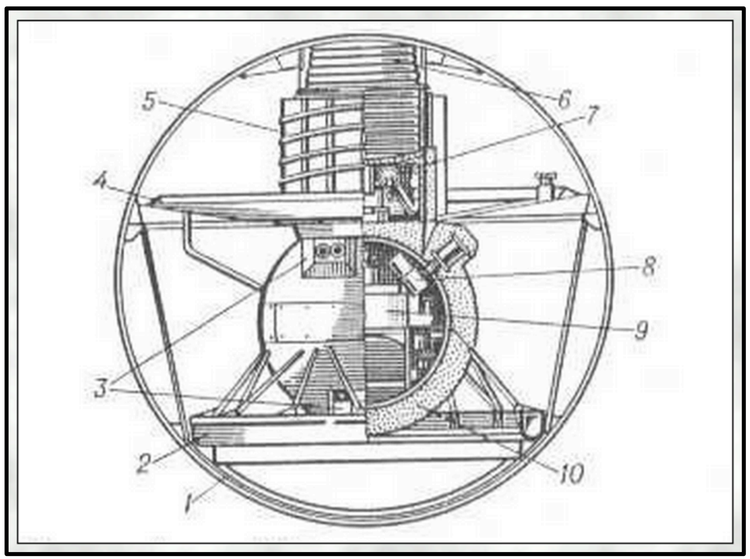
The last part from the following you-tube video:

https://www.youtube.com/watch?v=XLHH7JGd-Xo

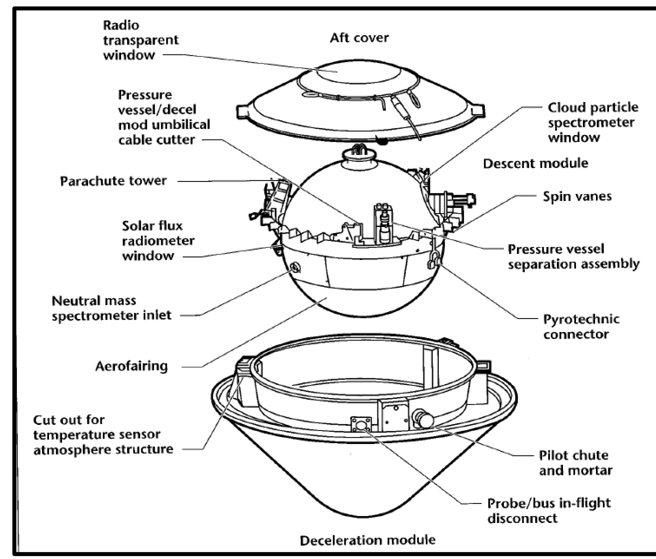
Missions	Entry System Fore-body Shape	Ballistic Coefficient (kg/m2)	Dia., m	Entry Ang
Venera (3 – 6)	Sphere	~ 450	1	(-62, -78)
Venera (7 and 8)	Circum-ellipsoid	~ (422 – 500)	1	~(-60 , -77)
Venera 9 - Vega 2	Sphere	~(139 – 170)	2.4	(-18, -23)
P-V Small Probes	45 deg. Sphere-cone	190	0.77	(-68.7, -41.5, -25.4)
P-V Large Probe	45 deg. Sphere-cone	188	1.42	-32.4

Venera 4

Venera 7/8



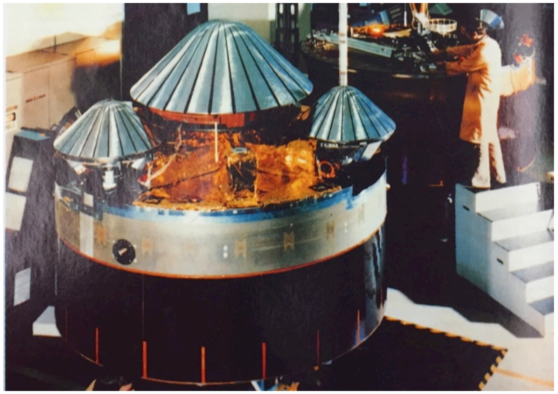
Venera 9 - Vega 2

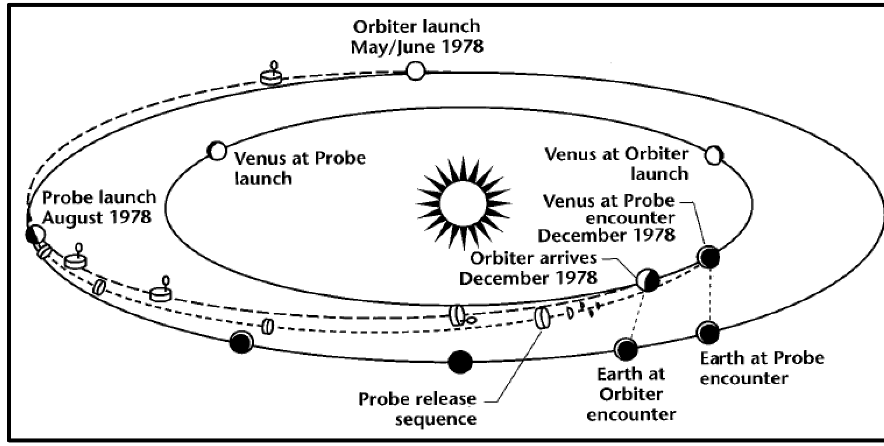


Pioneer-Venus

Pioneer-Venus: Entry Mission Segment

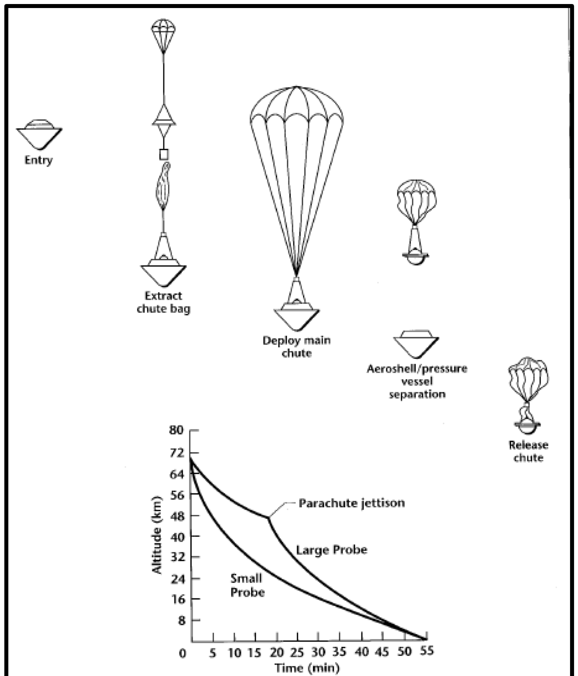
Bus with Large and Small Probes

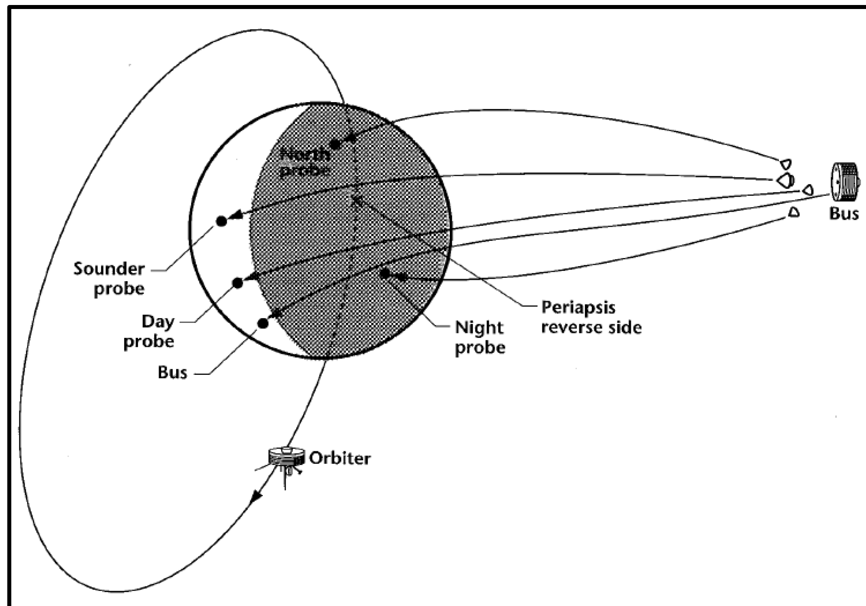




Interplanetary Trajectory

Entry and Descent Segment



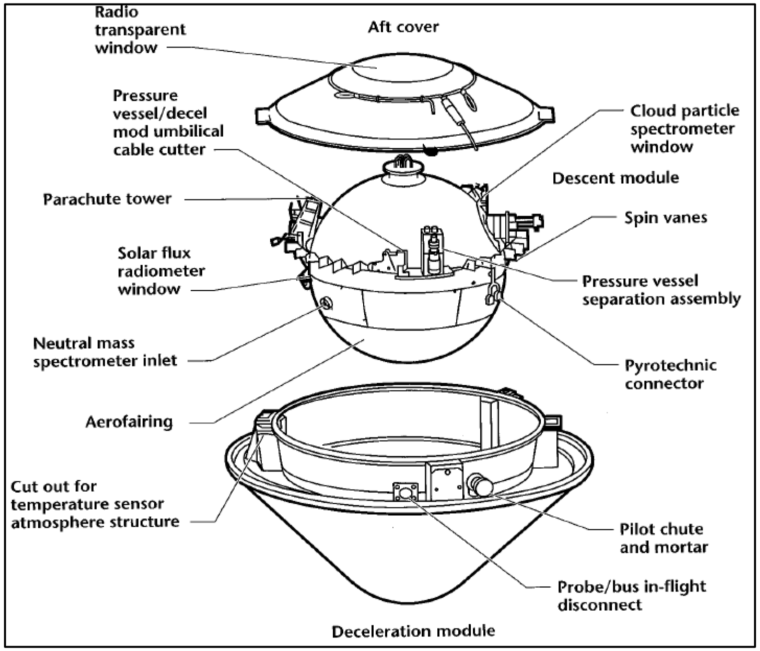


Probe Release and Entry

- Entry begins when atmospheric effects begin to impact the trajectory and the entry system begins to heat-up

Entry System

- Entry begins when atmospheric effects begin to impact the system
- Function of Entry System:
  - Safely deliver the “payload” from outside the atmosphere to a prescribed location within the atmosphere at prescribed condition (altitude, velocity and attitude)
    - Protects from the entry aerodynamic loads (rigid shell) and decelerates due to drag
    - Protects from entry heating (TPS) that results from deceleration
    - Achieve prescribed trajectory during entry as a result of aerodynamic stability
  - All of the Venus entry missions to-date have been ballistic entry
    - Primarily drag force (zero angle of attack)
  - Primary elements are
    - Heat-shield consisting of thermal protection system attached a structure
    - Back-shell consisting of the thermal protection system attached to structure

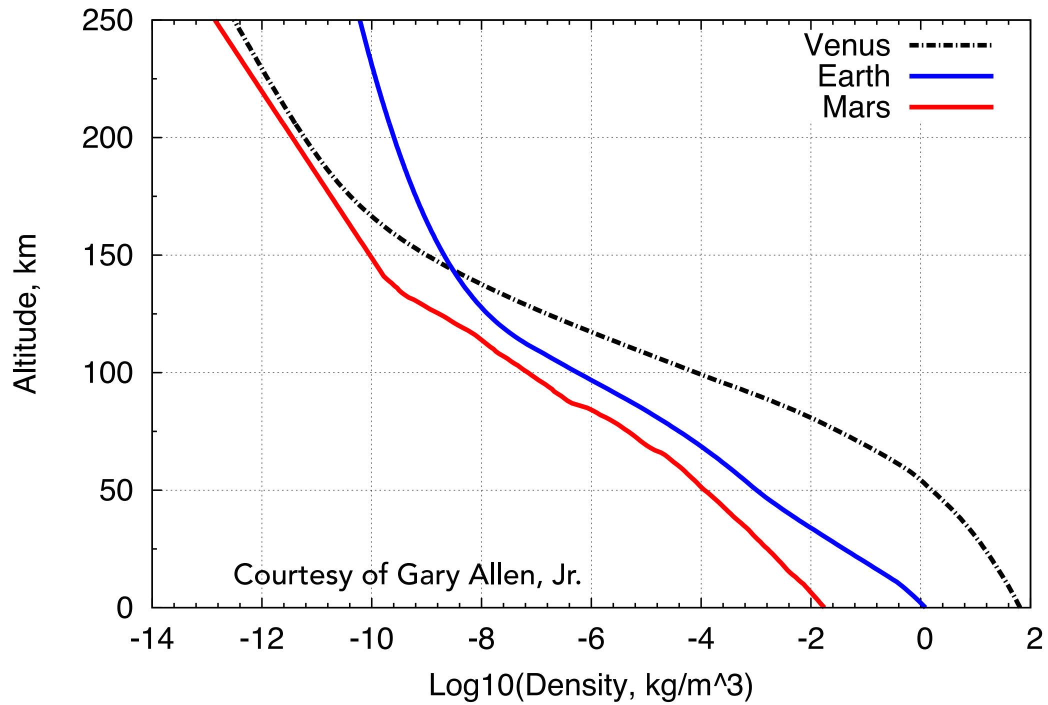


Entry System is designed to achieve stable flight and protect the scientific payload from heating-up

Atmosphere

- Venus and Earth sizes are similar; Escape velocities are (10.3 km/s vs 11.2 km/s)
  - Hyperbolic entry velocity at Venus range from (10.5 km/s – 12.5km/s)
- Between (150 km – 50 km) atmospheric density (Venus >> Earth or Mars)
- At ~ 60 km altitude Venus conditions are similar to conditions at sea level on Earth.
- Composition of Venus (predominantly CO_2) vs Air (N2, O2).
- The higher density profile and the composition effects results in much higher heating during entry at Venus compared to Earth.

Comparison of Atmospheric Density for Inner Planets



Aerodynamics: Static and Dynamic

- In order to determine the trajectory, the aerodynamics of the entry system across the range of flight conditions are required
  - Simple modified Newtonian aerodynamics is sufficient for early design and for 3-degrees-of-freedom trajectory construction

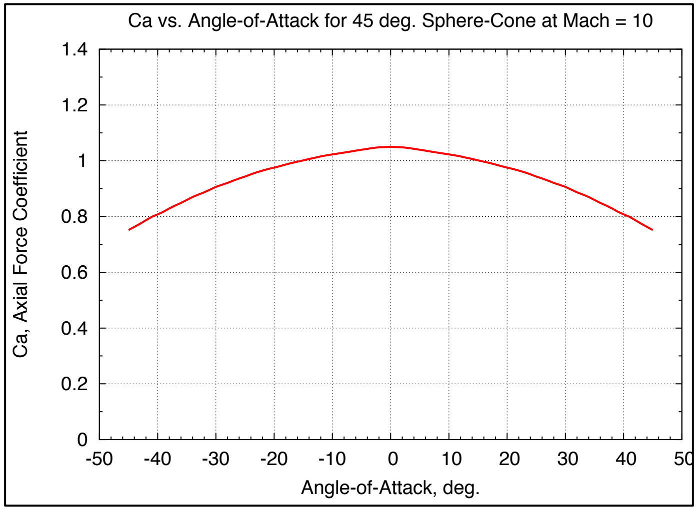
$$C_p = \frac{2}{\gamma_{inf} M_{inf}^2} \left[\frac{P_{wall}}{P_{inf}} - 1 \right]$$

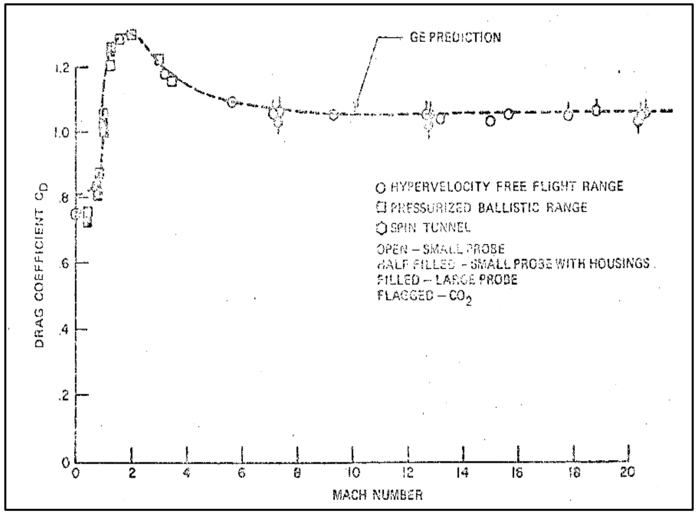
$C_p = C_{p\ max} * \sin(\delta)$, where δ is the local angle between the velocity vector and the geometric body, and $C_{p\ max}$ is the stagnation point pressure coefficient

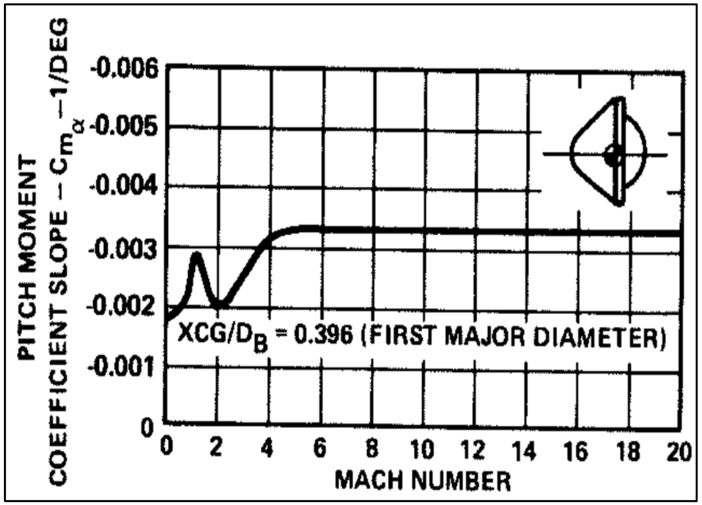
  - Detailed design, analysis and mission assurance will require a combination of ground testing and higher fidelity (CFD) simulation
  - Entry at Venus needs to account for CO_2 (real gas effects)
- Static and dynamic stability are a result of the balance between aerodynamic forces and the gravity (location and movement of the center of pressure with respect to center of gravity)
  - Static stability is easier to determine. Dynamic stability is more complex
    - C.G. and inertia of the system at entry
    - Non-linear flow physics - separation and real gas effects

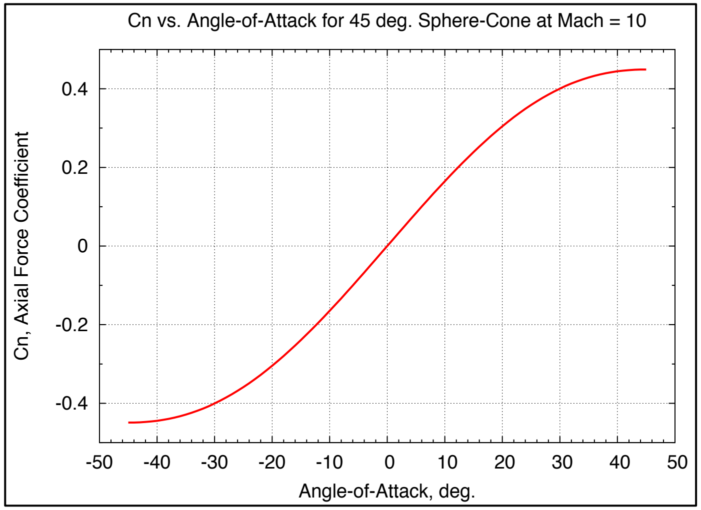
Aerodynamic Database for P-V

- The Aerodynamic database requires all of the aerodynamic coefficients to be available as a function of Mach number for 3-DOF trajectory simulations.



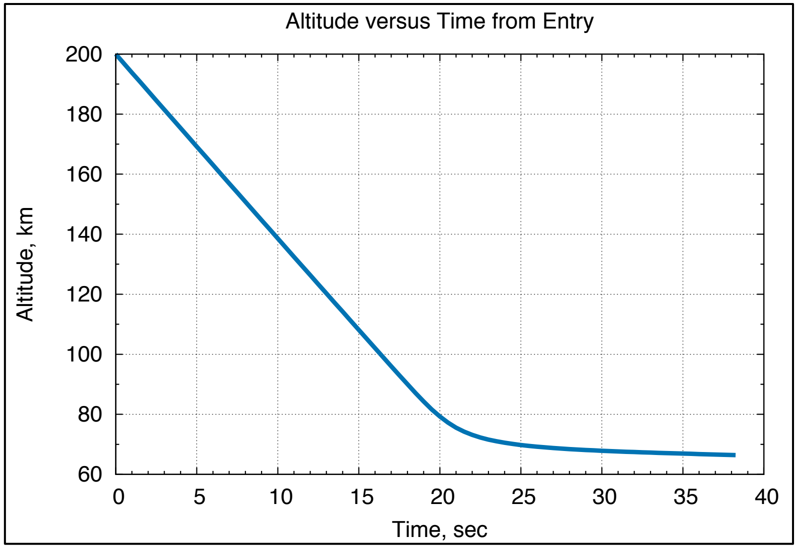


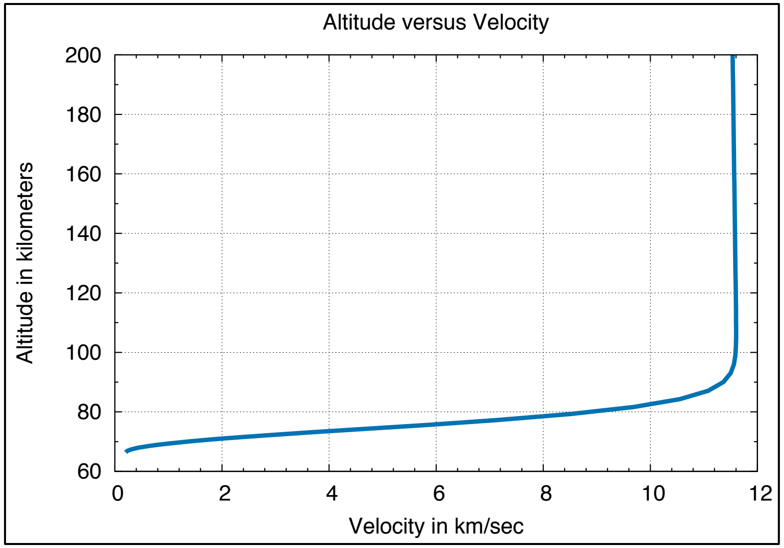




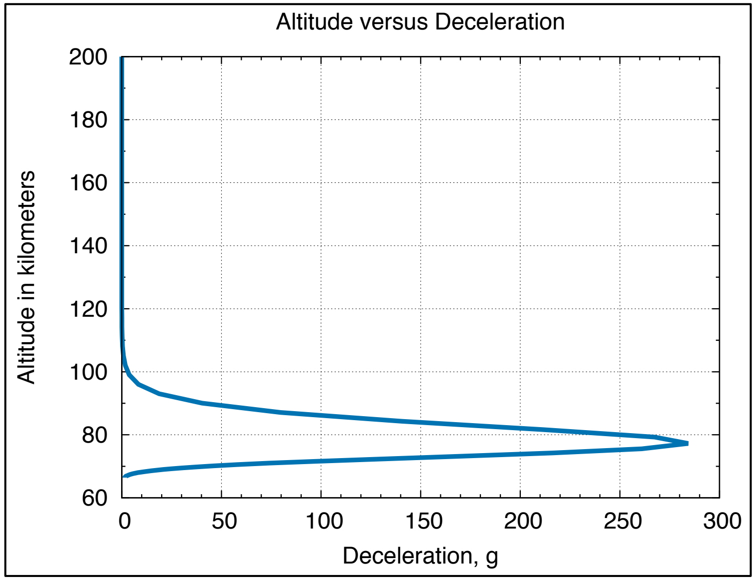
Trajectory

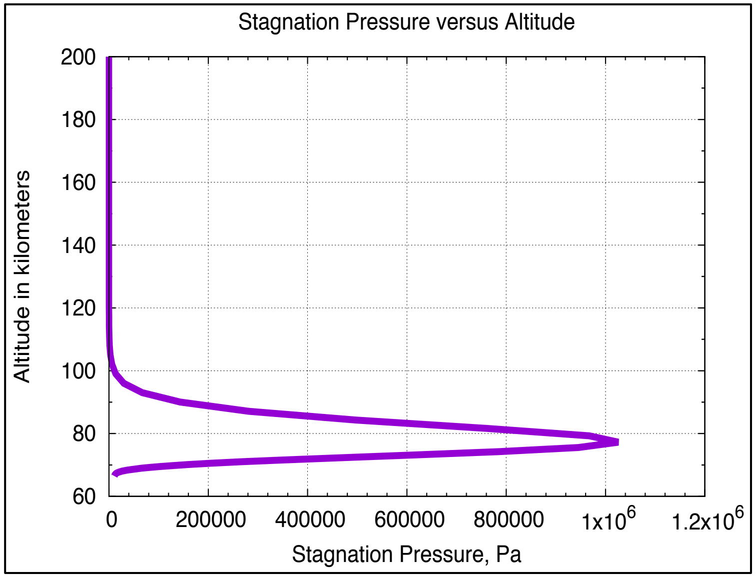
- The trajectory is determined based on entry velocity, entry flight path angle, ballistic coefficient and the aerodynamics of the entry system
- Typical hyperbolic entry from orbit at Venus ~(10.5 km/s – 12.5 km/s).
  - For entry from orbit, relative velocity can be lower by ~(1 km/s – 2 km/s)
- Entry flight path angle is defined as the angle between the velocity vector and the horizon at the atmospheric interface altitude.
- Ballistic coefficient is defined as (mass)/(Cd * A) where, m is the mass, Cd is the drag coefficient and A is the reference area.

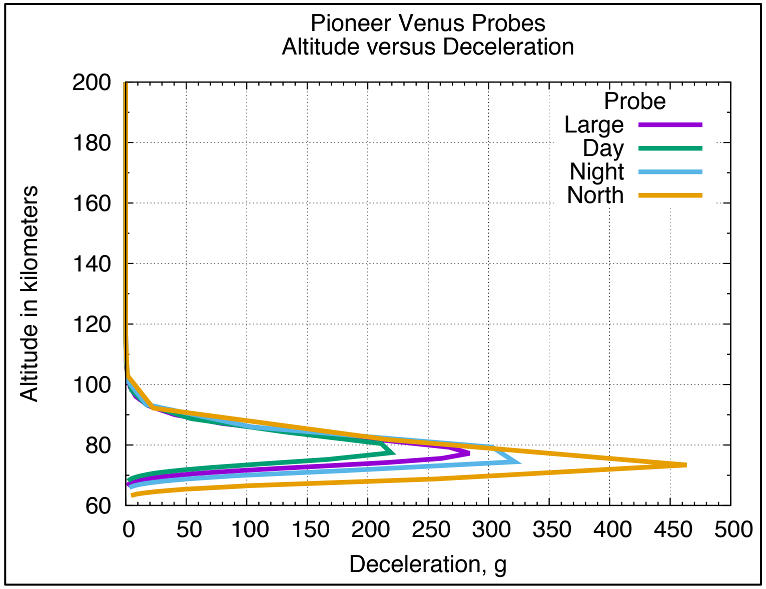




Entry Deceleration and Pressure



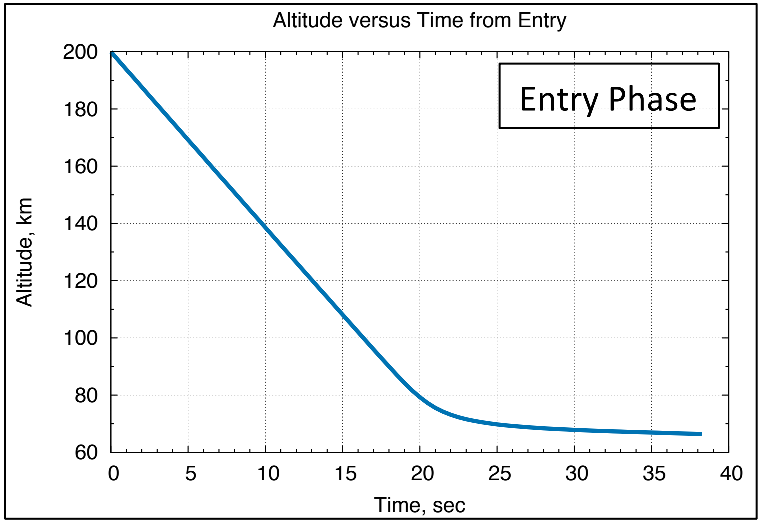


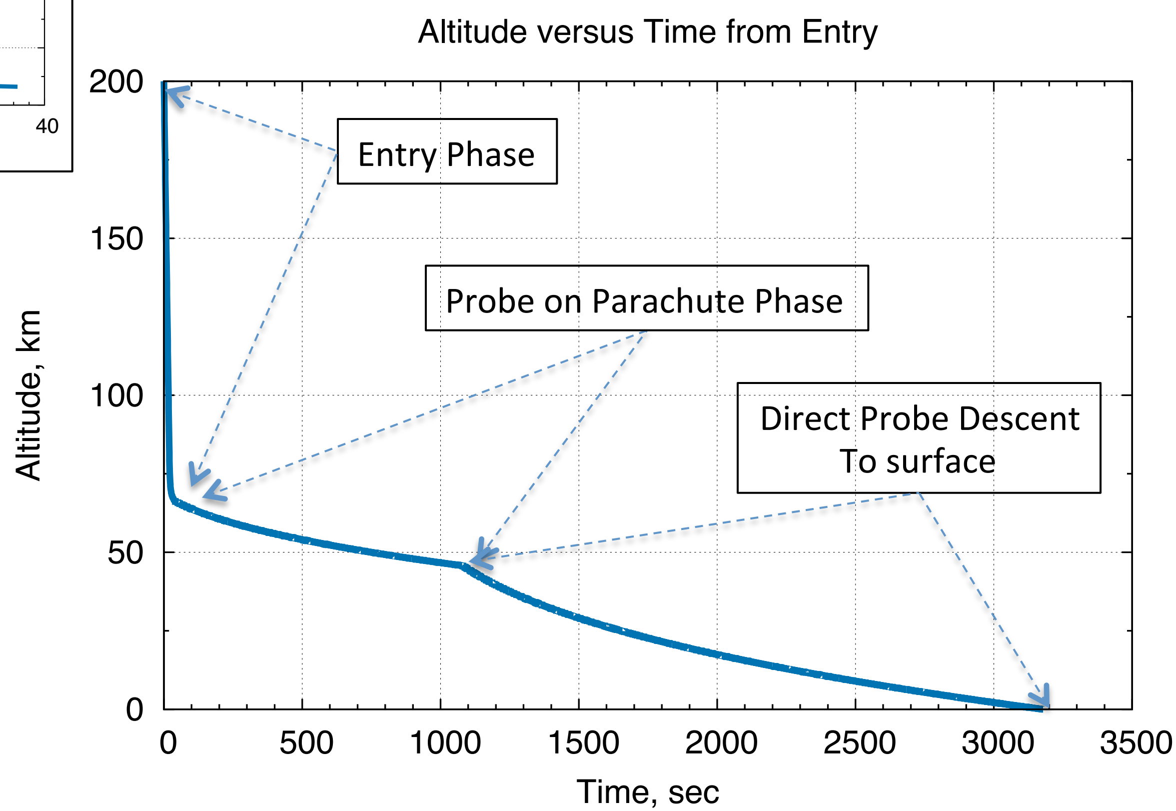


Missions	EFPA	BC (kg/m2)	Max G'load
P-V North Probe	-68.7	190	487
P-V Night Probe	-41.5	190	350
P-V Large Probe	-32.4	188	276
P-V Day Probe	-25.4	190	219

EFPA = Entry Flight Path Angle; BC = Ballistic Coefficient

Entry vs Descent Phases





Aerothermodynamics:

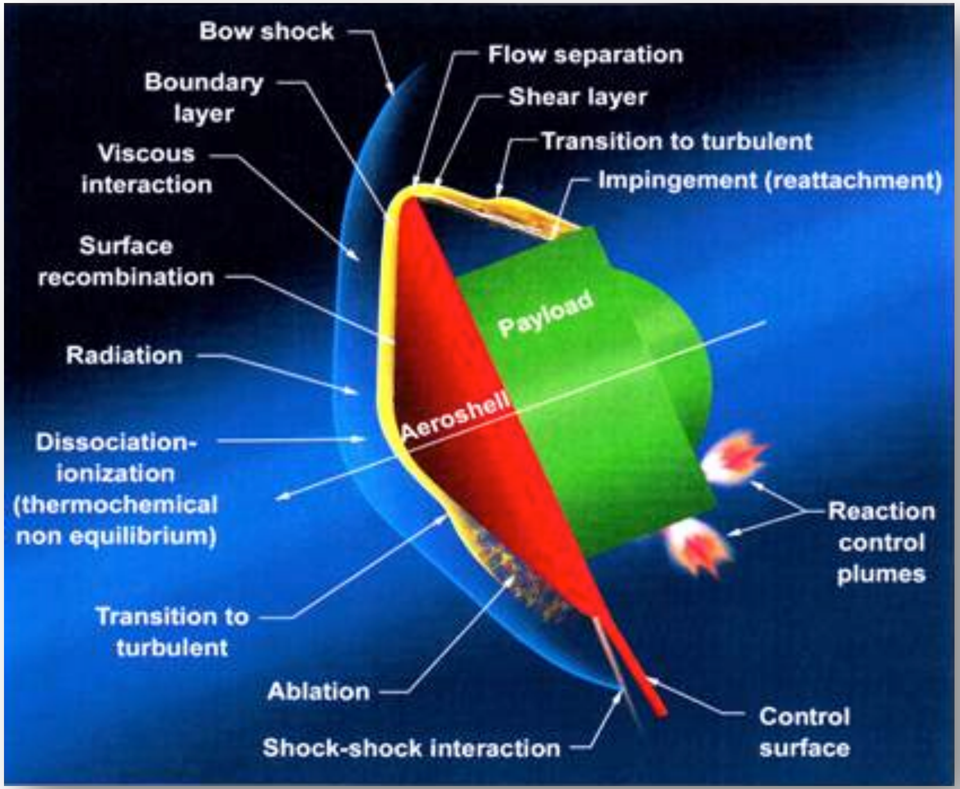
- Aerothermodynamics deals with the physics of high temperature flow around the entry system. Understanding of the flow physics through modeling, ground testing and flight data has led us to appreciate the hyper-velocity, reacting, thermo-chemical non-equilibrium flows. Current 3-D CFD simulation capabilities in combination with focused ground testing is allowing us to design TPS system with higher confidence.

Fore-body:

- Shock-layer and CO_2 dissociation at the shock front
- Chemical and thermal non-equilibrium
- Stagnation and acceleration of flow around the heat-shield
- Reacting boundary layer and surface recombination
- Turbulent transition
- Surface interaction
  - Shock layer radiative heating
  - Boundary layer convective heating
  - Ablation and pyrolysis gas injection

Back-shell:

- Complex separated flow, and shear layer interaction



Stagnation Point Heat-flux

- Stagnation point heat-flux can be computed with simplified engineering equations for preliminary design in assessing and selecting TPS material.

Stagnation point convective heating, q conv using Sutton and Graves

$$q_{conv} = k \cdot (\rho / r_n)^{0.5} \cdot V^3$$

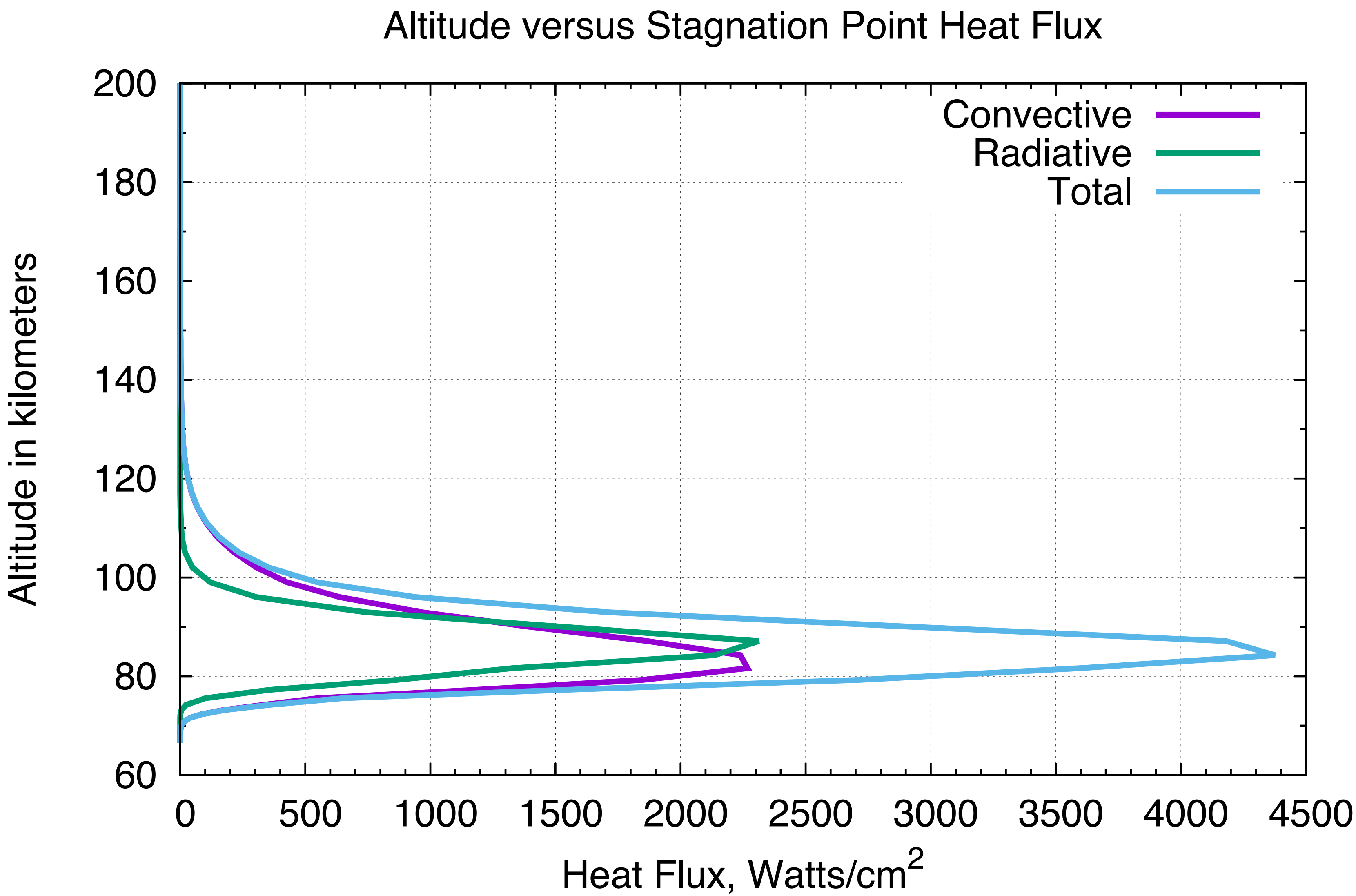
where k is a constant based on the planetary atmosphere, ρ is the free stream density, r_n is the nose radius, and V is the velocity

Stagnation-point radiative heat rate q_{rad} is computed using the Tauber-Sutton radiative heating correlation

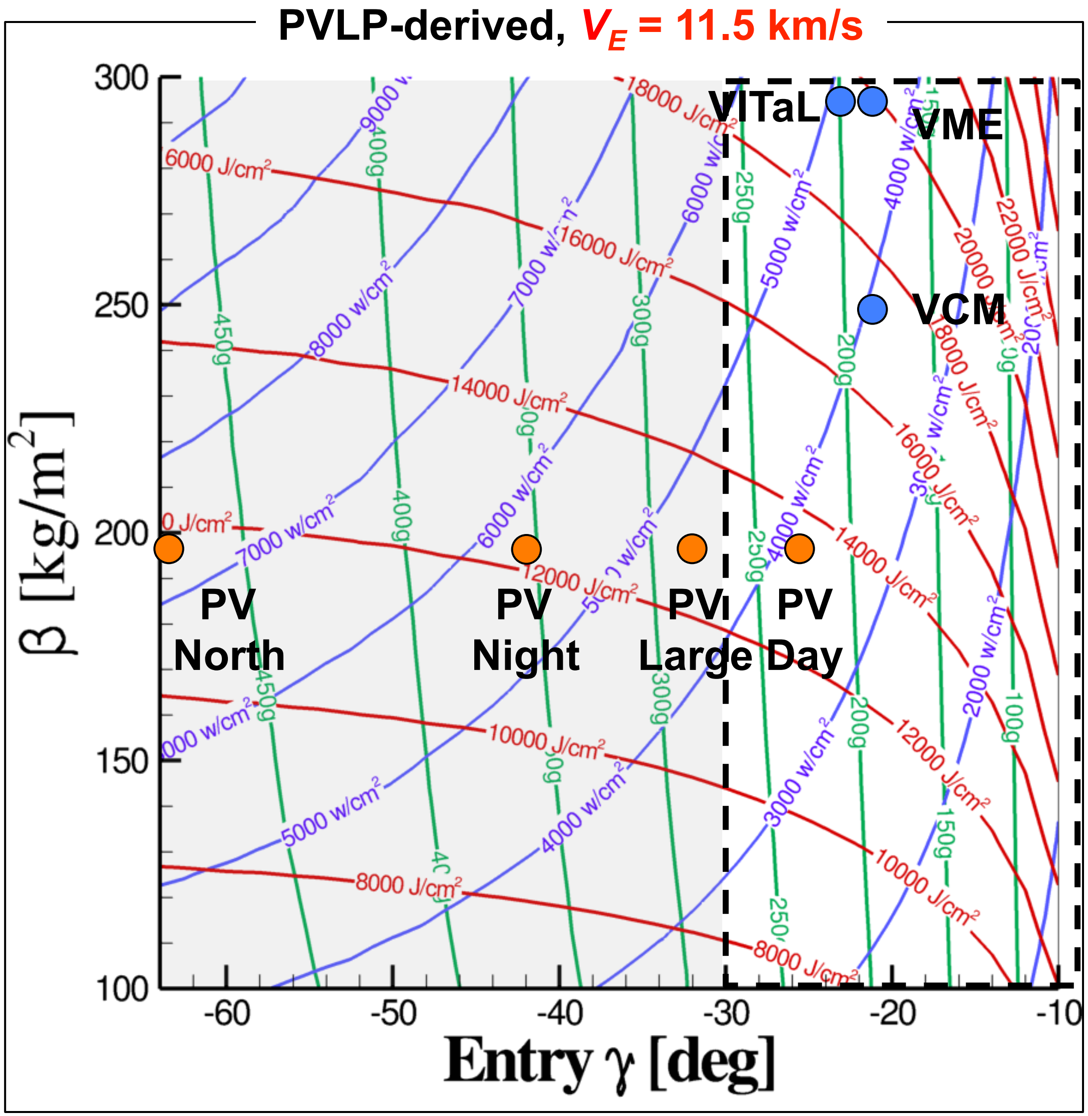
$$q_{rad} = C \cdot r_n^{a} \cdot \rho^{b} f(V)$$

where C is a constant based on the planetary atmosphere, r_n is the nose radius, ρ is the free stream density, and *f*(V) is a tabulated function for each planet (Tauber-Sutton).

P-V Large Probe Stagnation point heat-flux (convective, radiative and total)



- Integration of the heat-flux over the time gives integrated heat-load



- 3DOF survey of β_E-γ_E space for one entry velocity
- For entry angles between skip out ~(-8^0) and −15°, g' loads are less than 100.
- Peak stagnation point total heat-flux is a function of both entry flight path angle and ballistic coefficient.
  - higher β => higher heat-flux
- Heat-load increases significantly at lower entry flight path angle (proportional to time of flight)
- TPS selection depends on peak conditions where as TPS sizing (mass) depends on heat-load

Heating and TPS selection

Incident heating (Q_{IH}) is balanced by re-radiation by the hot wall (Q_{rerad}) and by the thermal protection system through conduction and process of ablation/ pyrolysis.

- TPS is selected and designed so that the heat via mass loss (ablation/pyrolysis) and the heat-conducted into the body are optimized for TPS mass with the constraint that the temperature at bond-line is maintained below specified temperature

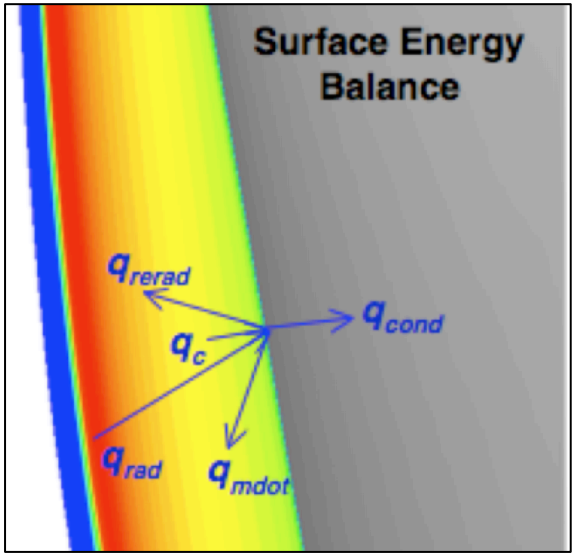
$$q_i = (q_{rerad} - q_{tps}) \text{ (energy balance)}$$

$$q_{rerad} = \varepsilon \sigma (T_{wall} - T_\infty)^4$$

$$q_{tps} = q_{cond} + q_{mass\ loss}$$

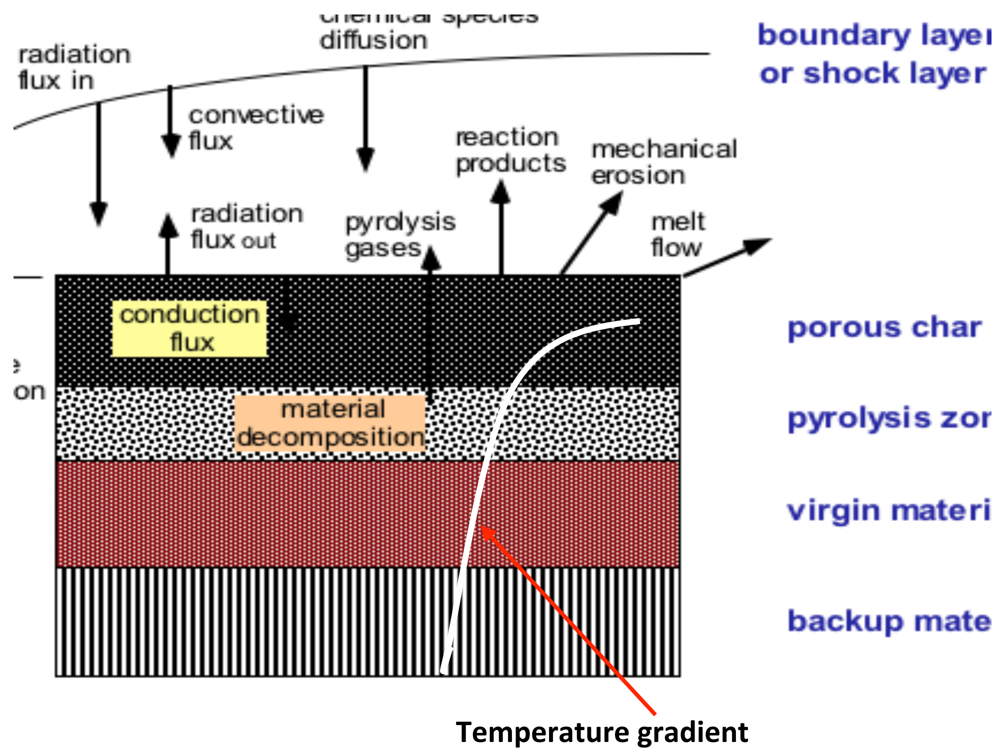
$$q_i = (q_{rad} + q_{con})$$

The T_{wall} is a function of the material and optical properties. Carbon and carbon char can reach much higher temperatures than silica based materials



How an Ablator Works?

- Hot gases in the boundary layer convectively heat the surface
- Radiant flux from the shock layer also heat the surface
- Heat is either re-radiated out or conducted into the surface
- The polymer in the composite begins to decompose and pyrolysis gases are formed
  - carbon remains and a char layer begins to form
- The thermal front moves through the material, causing more decomposition
- The pyrolysis gases, formed deeper in the composite are at a lower temperature than the near surface char, so as they flow through the char, they cool it
- The charred surface reacts (oxidation, sublimation, etc) with the boundary layer and material is removed, causing recession (this may be either exo- or endothermic)
- As the pyrolysis and gases formed at the surface blow into the boundary layer, they thicken it and reduce the convective heating



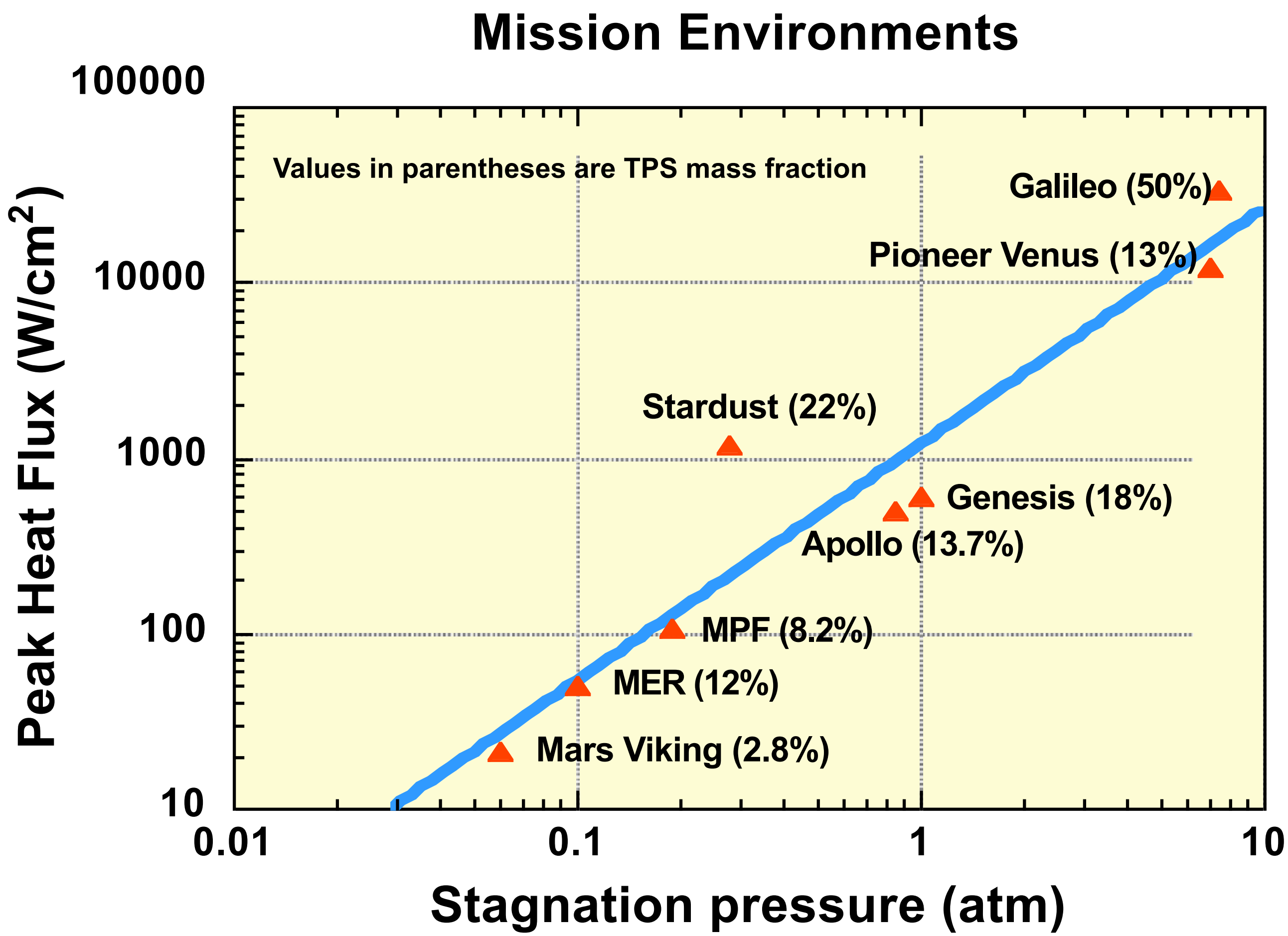
Design Consideration and TPS Selection

- Objective is *minimum* TPS mass with reliable performance
  - *Reliable performance* implies that material failure modes are well understood and environmental conditions leading to failure will not be encountered (or approached) for the selected mission
  - Low density materials are (typically) better insulators than high density materials
  - High density materials are (typically) better ablators than low density materials
- Ablation is good - it absorbs energy
  - Too much ablation may not be good if it leads to shape change that influences aerodynamics
- TPS selection involves a balance between ablation and insulation performance and manufacturability
  - Select the lowest density material that can handle* the range of environmental conditions (heat flux, pressure, shear, atmosphere)
  - Material should provide effective insulation for imposed heat load
  - Procedures for material fabrication, installation, inspection, etc., should be established and, preferably, demonstrate

*Material should have demonstrated reliability at extreme conditions of interest

Planetary Entry Missions and Flight Qualified TPS

- 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 ~30,000W/cm2 and 7 atm.)



Ablative TPS with Flight Heritage

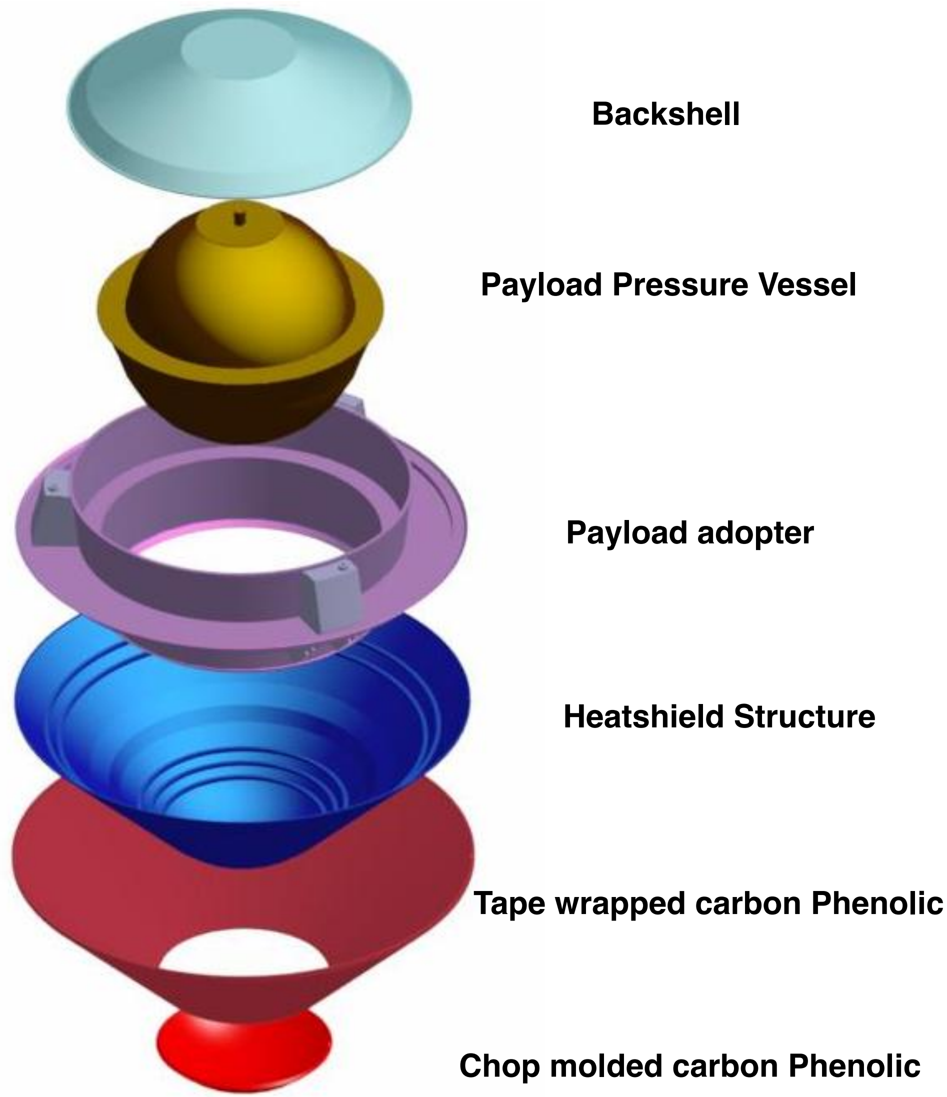
SLA-561V
Avcoat
PICA
Carbon-Carbon
Carbon Phenolic
ACUSIL II

Developmental TPS

Phen-Carb
SRAM
BLA
BPA
HEEET

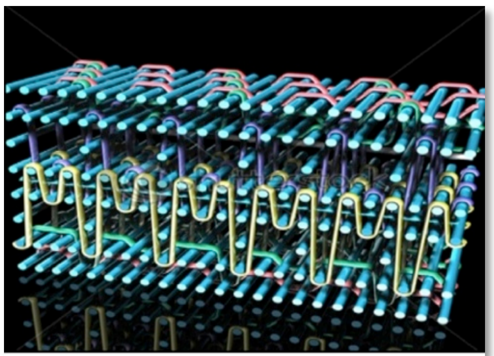
Carbon Phenolic

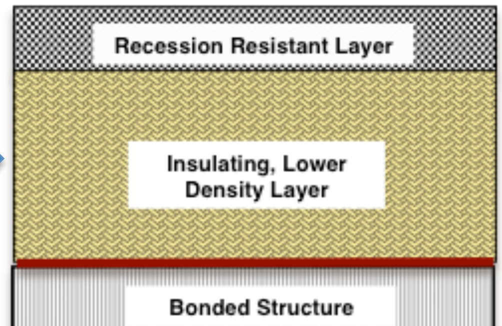
- Carbon Phenolic for entry systems was originally developed by DoD for ballistic missiles.
- NASA leveraged the DoD development for Galileo and P-V probes.
- DoD manufactured and used tape wrap carbon phenolic and NASA has to develop chop-molded carbon phenolic.
- Tape wrapped is used on the conical frustum and chop molded formed the spherical nose and the two parts were joined with a seam.

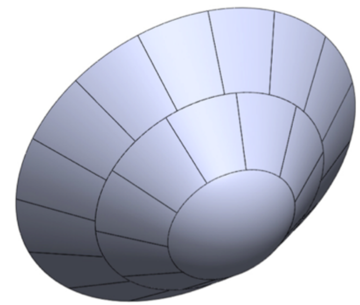


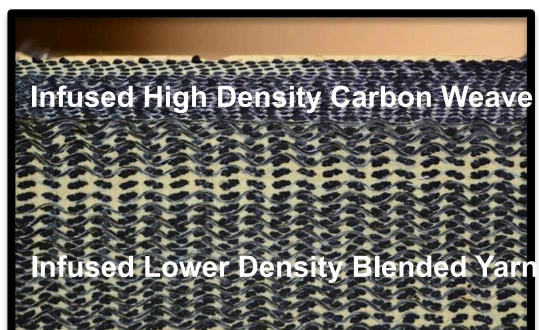
Heatshield for Extreme Entry Environment Technology (HEEET)

- HEEET is a dual-Layer 3-D woven material infused with low density phenolic resin matrix
  - Target missions include Saturn Probe and Venus Lander
  - Capable of withstanding extreme entry environments:
    - Peak Heat-Flux >> 1500 W/cm^2; Peak Pressure >> 1.0 atm.
  - Scalable system from small probes (1m scale) to landers (3m scale)
  - Sustainable – avoid challenges of C fiber availability that plague Carbon Phenolic

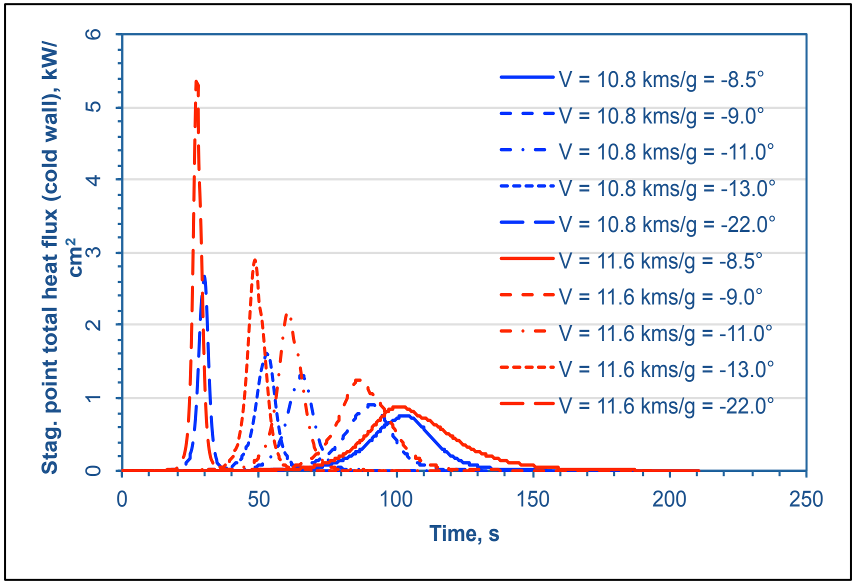


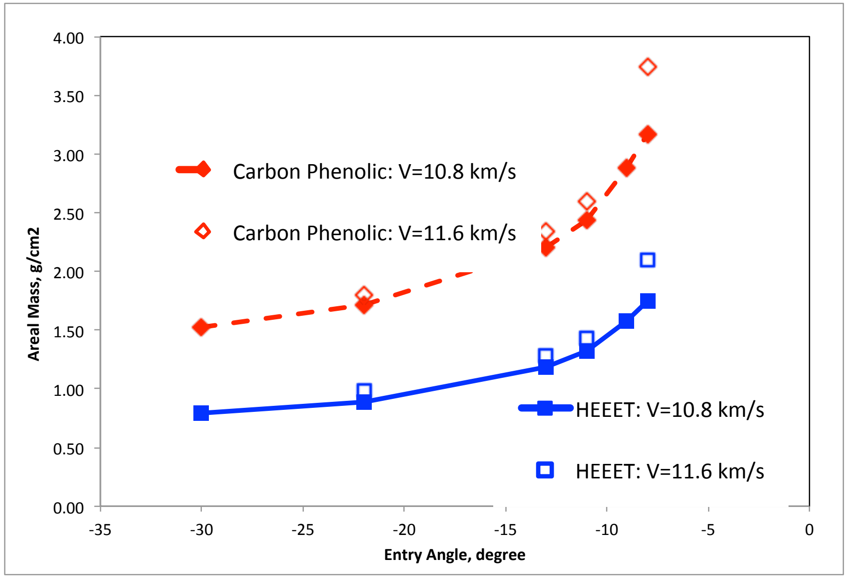






Venus Entry Probe Areal Mass Comparisons



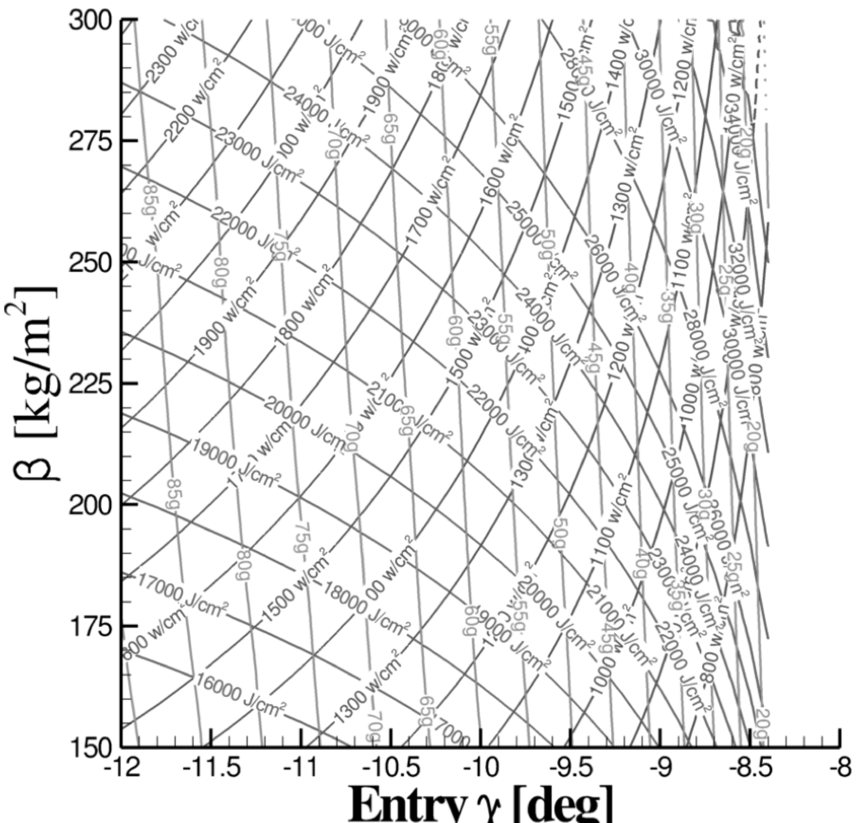


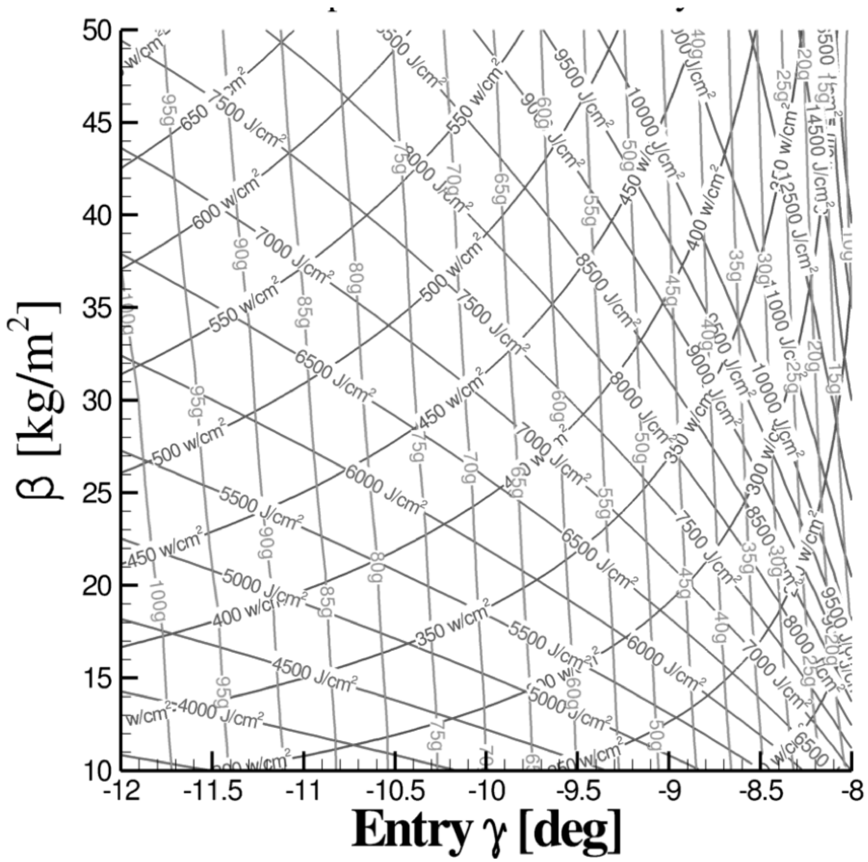
- Stagnation point analysis
  - 2750 kg, 3.5-meter diameter, 45-deg spherecone, nose radius of 87.5 cm, β = 272 kg/m^2
  - Entry velocities of 10.8 and 11.6 km/s. Entry flight path angles of -8.5^0, -9^0, -13^0, and -22^0 Areal mass of the 2-layer (HEEET) system has the potential for ~ 50% mass savings relative to heritage Carbon Phenolic
  - Sizing results are for zero margin utilizing preliminary thermal response model

Comparison of High and Low Ballistic Coefficient

Lowering both the ballistic coefficient and entry flight path angle reduces the peak conditions significantly:

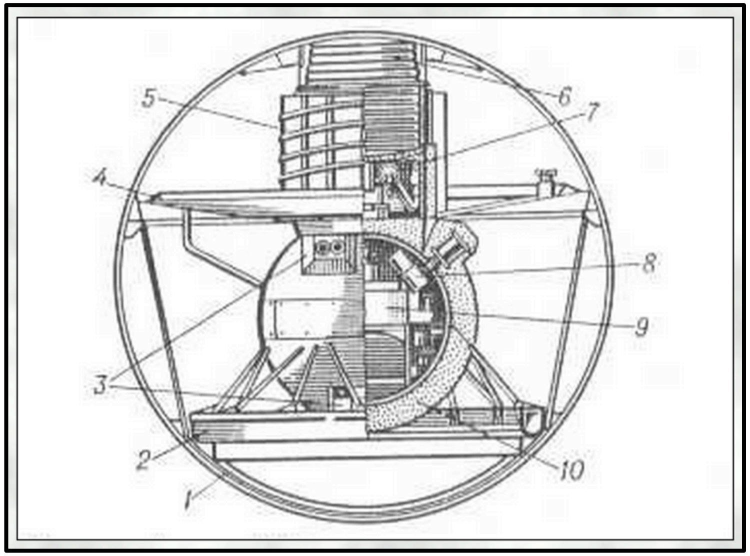
- Lowering ballistic coefficient lowers the peak stagnation heat-flux (peak stagnation pressure) and total heat-load
- Lowering the EFPA lowers the G’ load by an order of magnitude (~30) around ~9^0



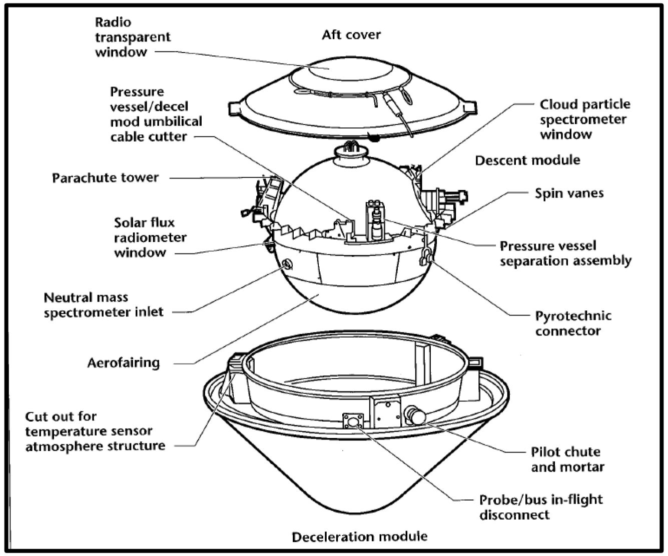


Design - Preliminary

- Once we have a Payload, we choose a shape that can provide sufficient drag during entry and determine the aerodynamic database.
  - CG of the entire entry system is constraint that we need to meet
- Depending on the Science and Instruments, we constrain the trajectory to a entry flight path angle
  - We know the structural load during entry
    - We can start to size the structure for the aeroshell
- Based on entry Velocity and entry flight path angle, entry peak-heat-flux, peak pressure, total heat-load are estimated at stagnation point.
  - If the geometry is large, turbulent transition may have to be taken in to account
- Once the heating profile is know, one can perform TPS sizing to estimate the TPS mass
- For preliminary design one may be able to assume a constant thickness TPS on the forebody and get mass estimate.
- For the back-shell similar process can be employed to get mas estimate.
- Structural mass and thermal protection system mass together now provides an estimate for the entry system component mass.



Venera 9 - Vega 2



Pioneer-Venus

Case Study: Venus Intrepid Tessera Lander (VITaL)

- National Research Council's 2010 Planetary Decadal Survey Inner Planets Panel commissioned NASA Goddard Space Flight Center (GSFC) to do a rapid mission architecture study
  - Conceive of Venus mission architecture capable of safe landing in one of the mountainous tessera regions of the planet on a budget compared to New Frontiers
  - Result: Venus Intrepid Tessera Lander (VITaL)

- Scientific capabilities:
  - surface chemistry and mineralogy measurements
  - atmospheric species measurements

- VITaL Reference:
  - Gilmore, M., Glaze, L, et al. "Venus Intrepid Tessera Lander (VITaL): Mission Concept Study Report to the NRC Decadal Survey Inner Planet Panel", 19 March 2010

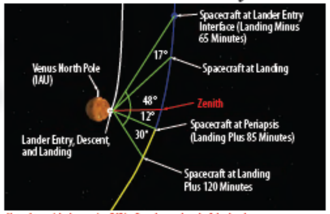
VITaL Fact Sheet

Venus Intrepid Tessera Lander
fact sheet

Mission Concept Study Report to the NRC Decadal Survey
Inner Planets Panel • March 15, 2010
Concept Maturity Level: 4 • Cost Range: Low End Flagship
GSFC • ARC

Nominal Mission:
- Atlas V 551 Launch Vehicle
- Type II trajectory

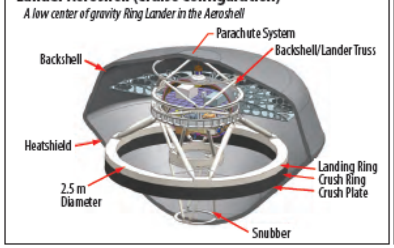
- Launch on 11/2/2021
- Venus fly-by 4/7/2022
- Descent/Landed science 7/29/2022



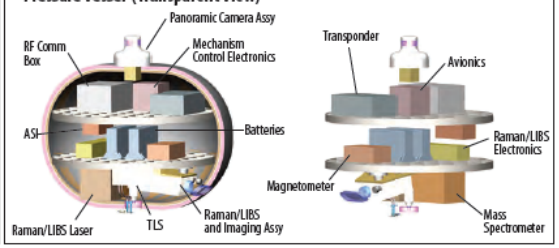
Note: At zenith the carrier S/C is directly overhead of the lander.

Mission Driving Science Objectives	Measurement	Instrument	Functional Requirement
Characterize chemistry and mineralogy of the surface.	Major, trace elements, mineralogy, NIR spectroscopy	Raman/LIBS; NIR (1.0 micron) descent imager below 1 km, Raman/LIBS context camera	Access to tessera terrain, > 25 *in situ* sample measurements, sample context images
Place constraints on the size and temporal extent of a possible ocean in Venus's past.	Measure D/H ratio in atmospheric water, mineralogy and major element chemistry of surface rocks.	NMS; TLS; Raman/LIBS	*In situ* sampling of the upper and lower (<16 km) atmosphere. Access to and measurement of tessera terrain.
Characterize the morphology and relative stratigraphy of surface units.	Visible and NIR observations of multiple surface units at cm to m scale spatial resolution.	NIR (1.0 micron) descent imager and surface panoramic camera with ~5 filters from 550-1000 nm.	Position of cameras to image the surface, while accommodating expected slopes, platform stability for clear images.

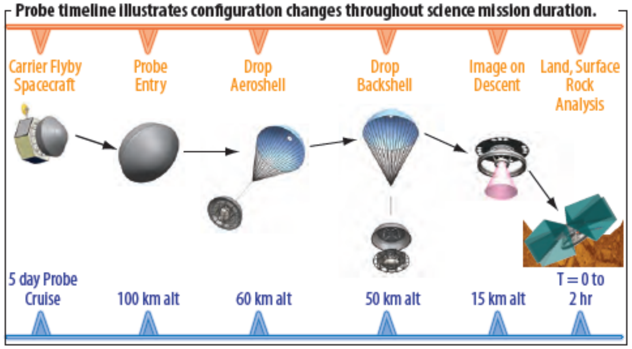
Lander Aeroshell (Cruise Configuration)
A low center of gravity Ring Lander in the Aeroshell



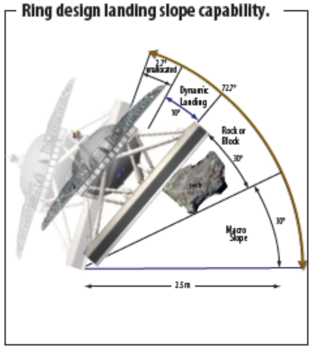
Pressure Vessel (Transparent View)



Probe timeline illustrates configuration changes throughout science mission duration.



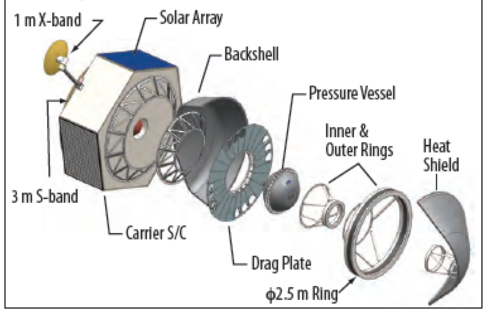
Ring design landing slope capability.



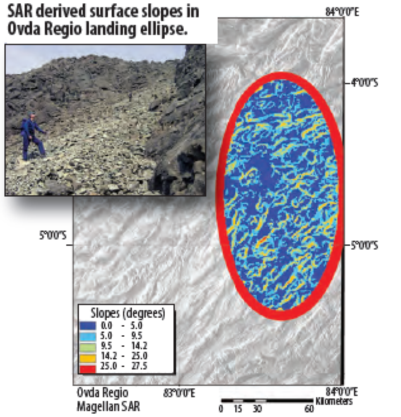
Venus Intrepid Tessera Lander
fact sheet

- 2 -

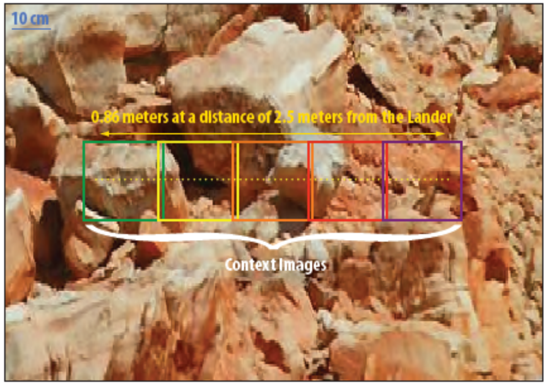
Exploded view of Carrier Spacecraft, Aeroshell, and Lander

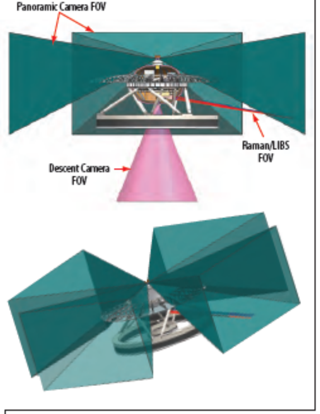


SAR derived surface slopes in Ovda Regio landing ellipse.

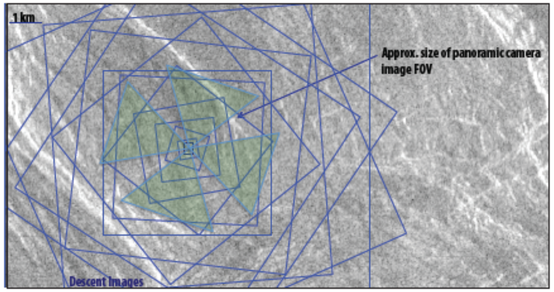


Raman/LIBS Survey Measurements and Context Images





Descent and Panoramic Imagery

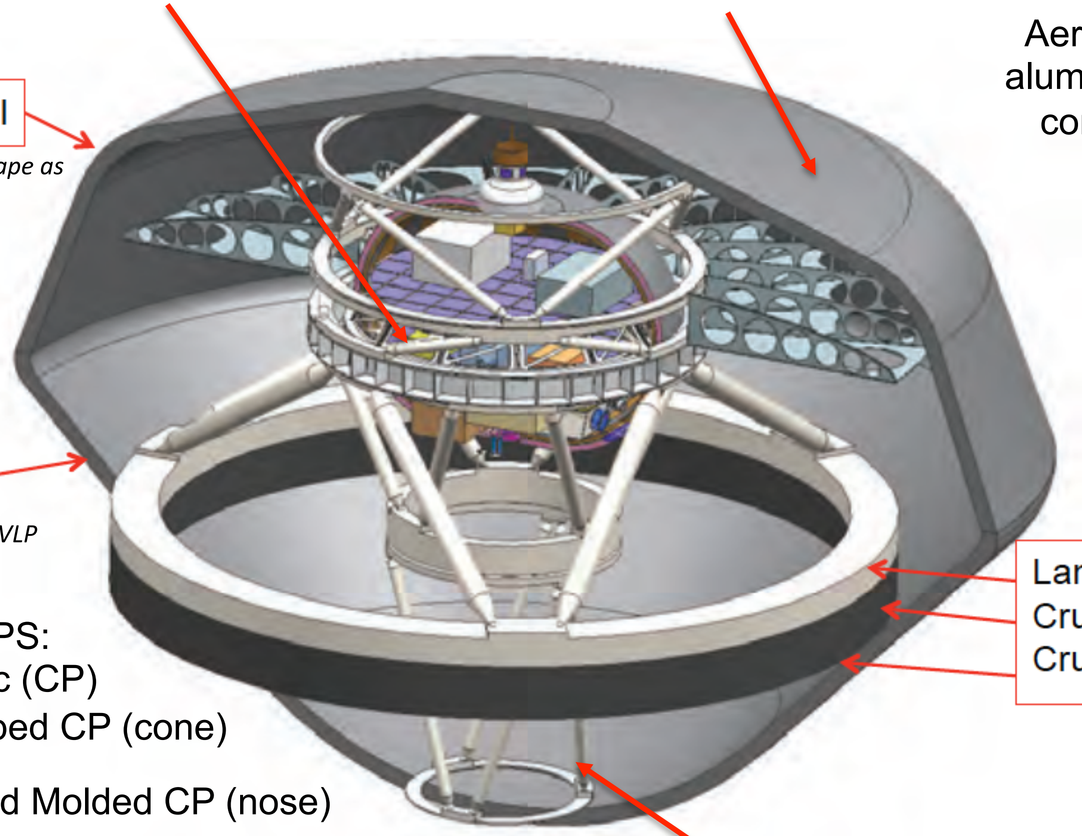


Mass Breakdown

Component	CBE [kg]	Allow [%]	Max Mass [kg]
Lander	1051	30%	1366
Lander Science Payload & Accum.	48	30%	63
Lander Subsystems	1002	30%	1303
Mechanical/Structure	283	30%	368
Landing System	603	30%	784
Thermal	67	30%	87
Power	12	30%	16
Avionics	28	30%	36
RF Comm	9	30%	12
Aeroshell	1051	30%	1379
Spacecraft	846	30%	1100
Satellite *(S/C + Probe)* Dry Mass	2948	30%	3845
Satellite Wet Mass	3299	30%	4200
LV Throw Mass available to lift Wet			5141

VITaL Probe Design

Payload: 1051 kg lander **Aeroshell: 1051 kg**



Entry Mass = Aeroshell + Payload = 2102 kg

Why does VITaL look the way it looks?

- Choosing carbon phenolic drives a system design toward higher heat rates in order to minimize TPS mass
  - Carbon phenolic is an awful insulator- you want get subsonic as soon as possible so you can jettison the heatshield before the bondline reaches its design-limit temperature (typically 500 ºF)
    - Otherwise the carbon phenolic must be made thicker so the thermal soak to the bondline takes longer
  - Drives you to steeper entry flight path angles
    - higher heat rates, lower heat loads (less carbon phenolic), higher g-loads

- The 45º sphere cone is a mass efficient aeroshell geometry when the mission is constrained by carbon phenolic as the heatshield TPS
  - Higher peak heat rates compared to more blunt aeroshell
    - Also has better static stability than more blunt aeroshell
  - Entry at Venus is dominated by radiation
    - 45 sphere cone has reduced radiative heating on the conical frustum compared to more blunt aeroshell
  - The challenges:
    - Sub-optimal volume/packaging efficiency (but it might not matter to the science payload)
    - High peak g-load during entry (200 g's for VITaL)
    - Higher aeroshell structure mass

VITaL Aeroshell Mass Optimization

- Minimize aeroshell mass with a g-load constraint of 200g
  - Lower G-load eases instrument qualification and minimizes aeroshell structural mass
  - Primary driver of G-load: Entry Flight Path Angle (EFPA)
    - Steeper: rapid deceleration → higher g-load
    - Shallower: slower deceleration → lower g-load
  - Minimize TPS mass → drives you to steeper EFPA
  - Result: -23.35º EFPA (11.3 km/s entry velocity)

VITaL Aeroshell Component Masses

Aeroshell Element	Mass (kg)
Backshell structure	224
Backshell TPS	69
Heatshield structure	269
Heatshield TPS	449
Parachute	40
Total	1051

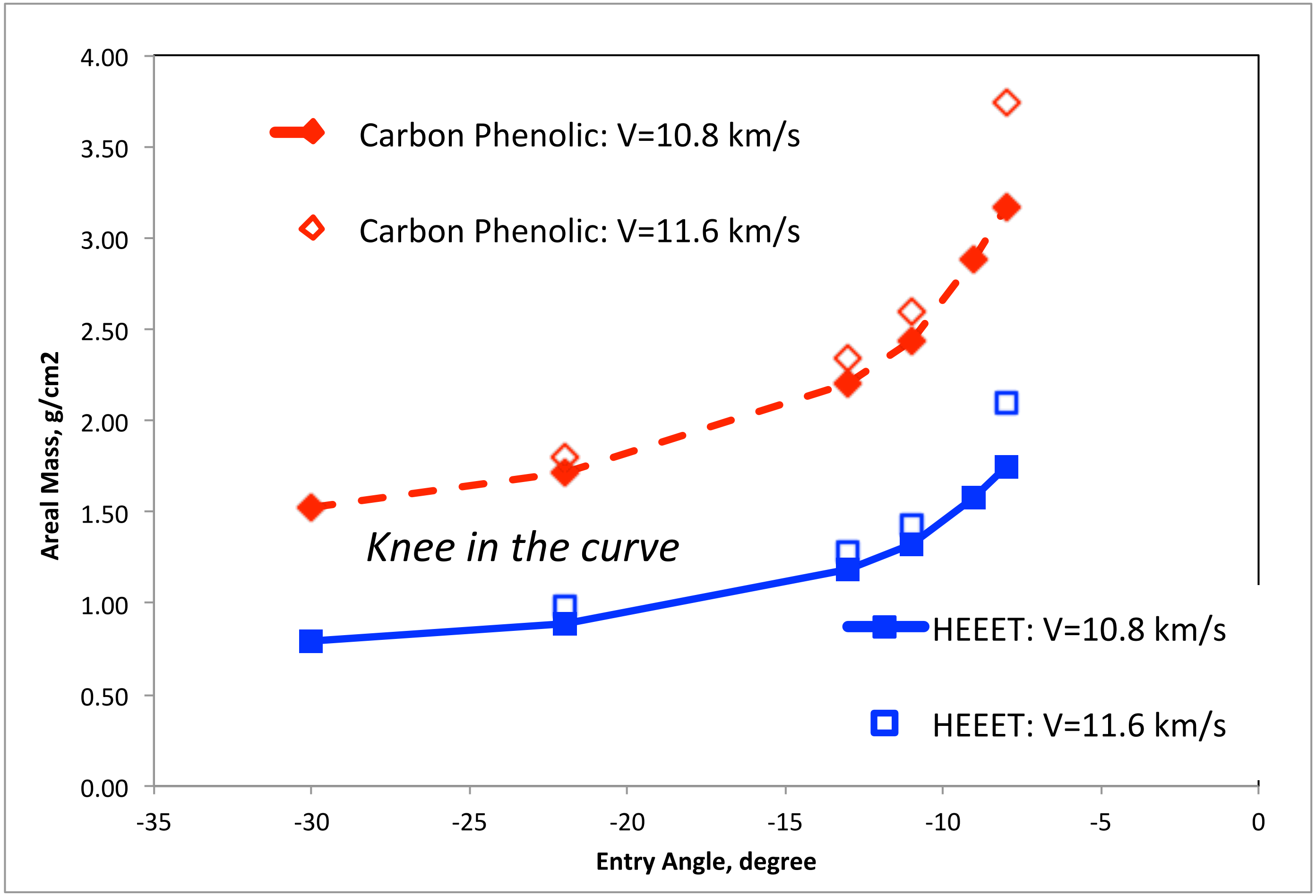
Subsystem Masses

Subsystem	Mass (kg)	% of Aeroshell Total
Structure Total	493	47%
TPS Total	518	49%
Heatshield Total	718	68%
Backshell Total	293	28%

Structure Mass ≈ TPS Mass
Heatshield TPS is 87% of total TPS Mass

Driving home the -23° EFPA

- TPS areal mass vs. entry flight path angle



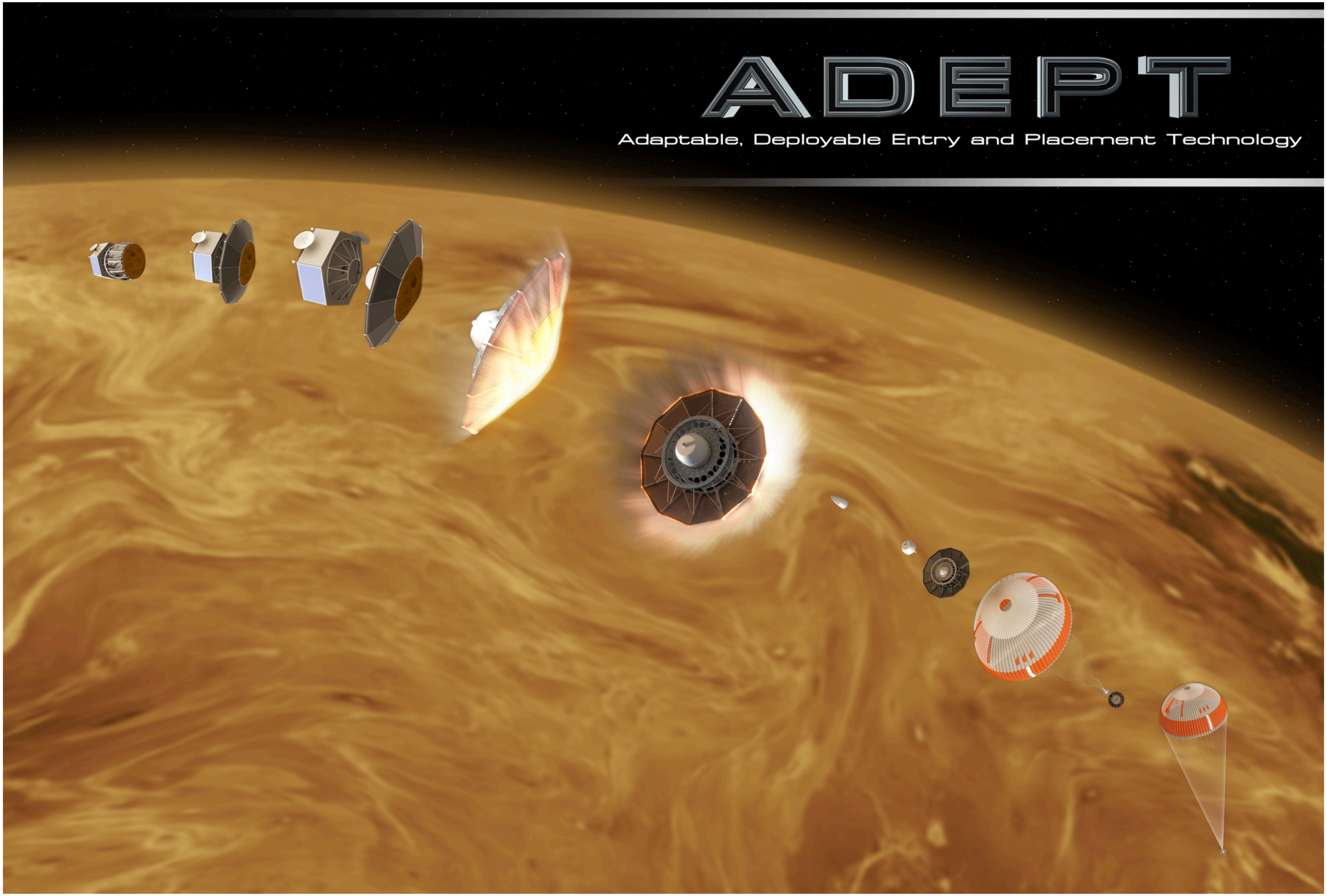
Case Study: ADEPT-VITaL

- ADEPT is a deployable entry system that lowers the ballistic coefficient by increasing drag area
- In 2013, NASA conducted a study to explore the system benefits of using ADEPT as the entry system for VITaL (instead of a 45-deg sphere cone)
- Motivation
  - Enable systems sensitive to peak g-load, specifically ASRG and improved science instruments
  - Identify environments that would bound ADEPT mission applications and develop design solutions
    - Venus is most extreme entry application for ADEPT
- Expectation:
  - Reduce peak g-load by an order of magnitude compared to baseline
  - Eject VITaL from the aeroshell at a higher altitude compared to baseline (earlier start to science phase)

References

- Venkatapathy, E., Glaze, L., et al, "ADEPT-VITaL Mission Feasibility Report: Enabling the Venus In-Situ Explorer Mission with Deployable Aeroshell Technology," Version 2.1, 1 August 2013.
  - Lots of detail (119 pages). Publically Released. Request copy from Brandon Smith (brandon.p.smith@nasa.gov)
- Smith, B. et al, "Venus In Situ Explorer Mission Design using a Mechanically Deployed Aerodynamic Decelerator," 2013 IEEE Aerospace Conference, Big Sky, MT, March 2013.
  - More concise version of the feasibility report (18 pages). Available on IEEE Xplore.

ADEPT-VITaL Mission Concept Video

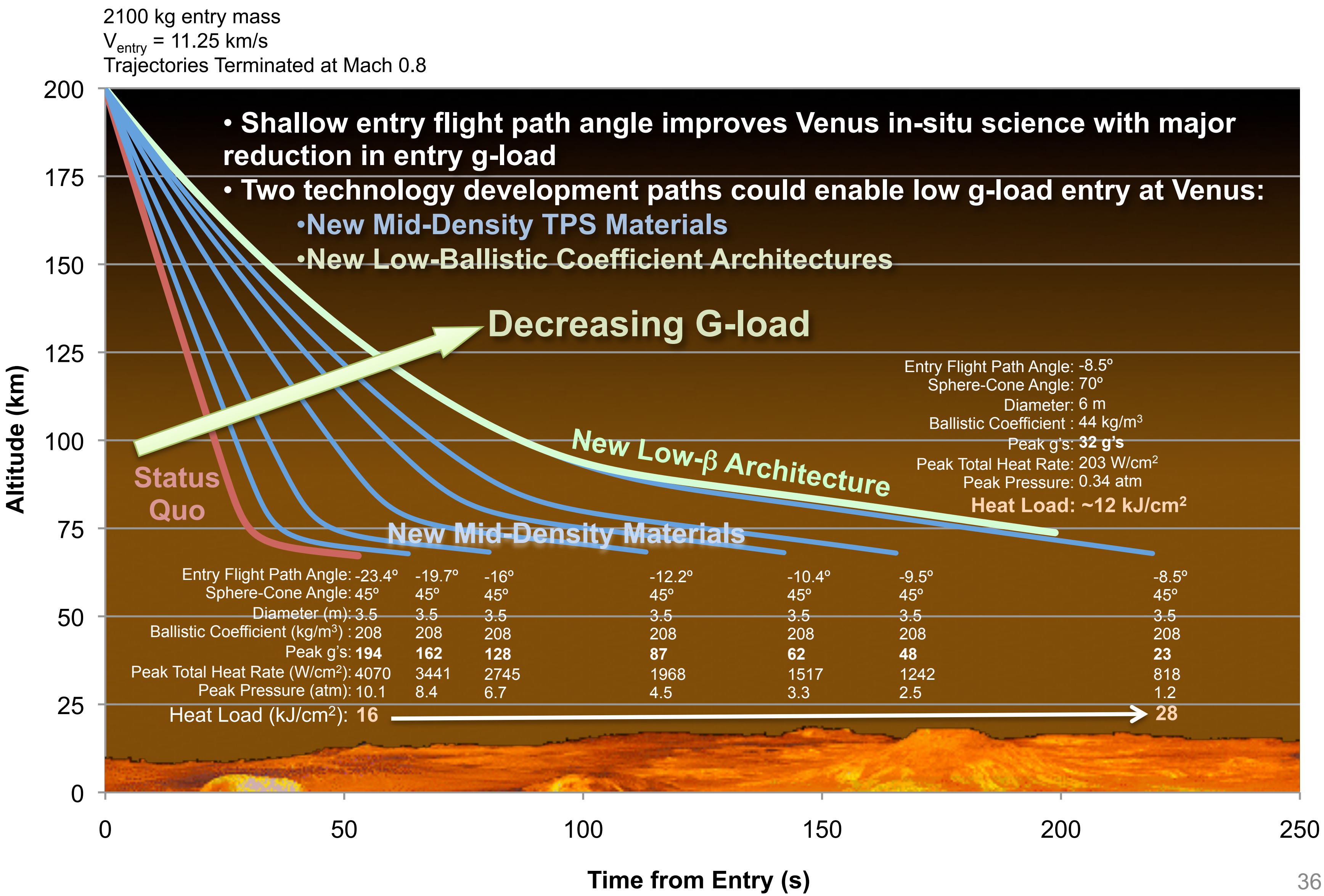


Mass Comparison

- VITaL mass is reduced by 23% when using ADEPT due to lower structural mass as a result of lower peak g-load
  - Same science capability as baseline VITaL mission

Item	Baseline VITaL Mission (kg)	ADEPT-VITaL Mission (kg)
VITaL	1051	814
Lander Science Payload	48	37
Lander Subsystems	1003	777
Entry System	1051	807
Entry Mass (Entry System + VITaL)	2102	1621

Venus Entry Technology Summary



Concluding Remarks

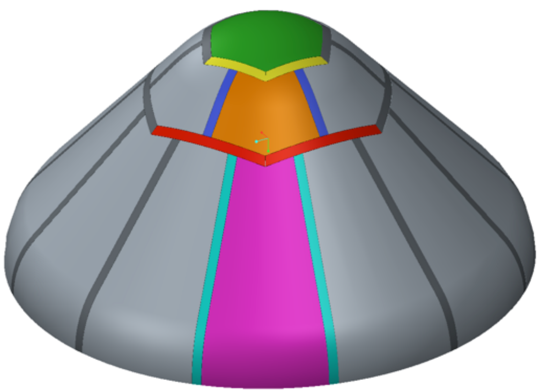
- This section of the course covered:
  - What happens during entry?
  - What is an entry system (or aeroshell)? What is its function?
  - What entry physics aspects that governs the interaction of the atmosphere with the entry system?
  - How do we design an aeroshell? Preliminary to detail?
    - How does one select the shape of the aeroshell?
    - How is the aerodynamic and entry heating are determined?
    - Why do we need ablative Thermal Protection System?
    - How does one choose the TPS?
  - What are recent developments in technology that can enable future science missions?

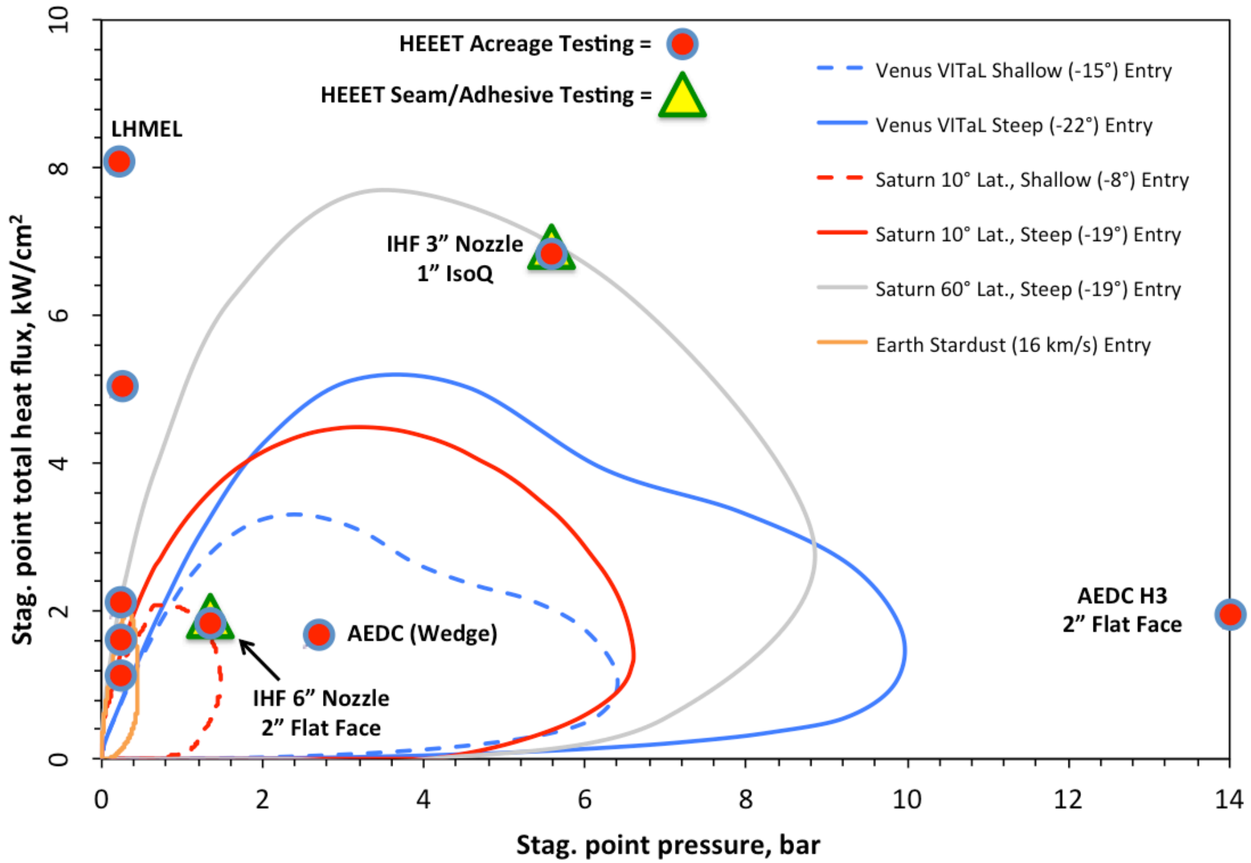
Processes that consume mass – some effective in thermal management and others not

- Melting (metals, glass, ceramics, etc.)
  - Heat of fusion (not very significant)
  - $M(s)^* \Leftrightarrow M(l)^*$
- Vaporization (liquid layer from melted metals, glass, ceramics)
  - Heat of vaporization
  - $M(l)^* \Rightarrow M(g)^*$
- Oxidation (graphite, carbon chars, etc.)
  - Exothermic
  - $M(s)^* + O_2(g) \Rightarrow MO_2(g)$
- Sublimation
  - Heat of sublimation (can be significant)
  - $M(s)^* \Rightarrow M(g)$
- Spallation
  - Mass loss with minimal energy accommodation

Mission Relevant Environment Thermal Testing

- **Stagnation point environments from Venus, Saturn and Earth entry missions**
  - Venus steep entry has the highest surface pressure loading
  - Acreage HEEET has been extremely robust and have not failed at any of the conditions tested to-date. Carbon Phenolic tested side-by-side shows failure as anticipated





Historical Perspective: Past Venus Entry Missions

Table 1. Past successful Venus entry missions. [1]-[6]

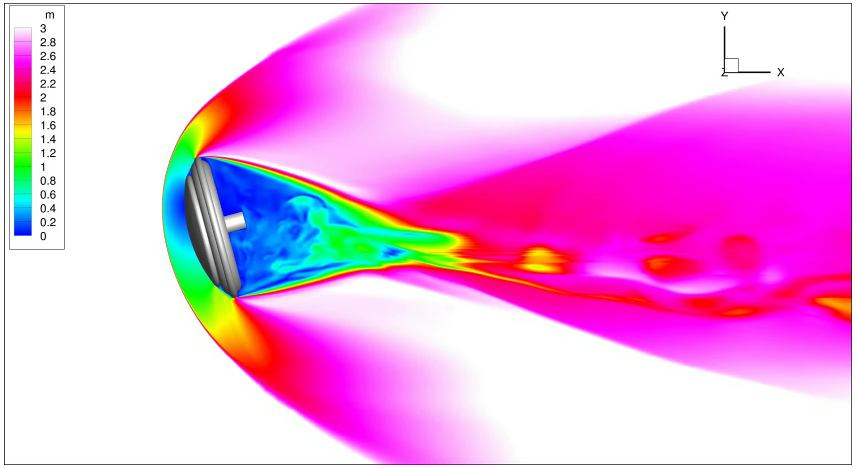
Year	Mission	Nation	β (kg/m²)	γ (deg.)	V_{entry} [i] (km/s)	Shape	Dia. (m)	n_{max} [ii] (g's)	q_{max} [ii, iii] (kW/cm²)
1967	Venera 4	USSR	519	-78	10.7	Sphere	1.0	450	9.66
1969	Venera 5	USSR	549	-62 to -65	11.2	Sphere	1.0	440-450	13.5
1969	Venera 6	USSR	549	-62 to -65	11.2	Sphere	1.0	440-450	13.5
1970	Venera 7	USSR	677	-60 to -70	11.2	Circumellipsoid	1.0	422-452	17.0
1972	Venera 8	USSR	670	-77	11.6	Circumellipsoid	1.0	500	30.0
1975	Venera 9	USSR	367	-20.5	10.7	Sphere	2.4	150	3.04
1975	Venera 10	USSR	367	-23	10.7	Sphere	2.4	170	3.37
1978	Pioneer-Venus-North	USA	190	-68.7	11.5	45 deg. Sphere-cone	0.7653	487	10.6
1978	Pioneer-Venus-Night	USA	190	-41.5	11.5	45 deg. Sphere-cone	0.7653	350	7.8
1978	Pioneer-Venus-Day	USA	190	-25.4	11.5	45 deg. Sphere-cone	0.7653	219	5.2
1978	Pioneer-Venus-Large	USA	188	-32.4	11.5	45 deg. Sphere-cone	1.4228	276	6.9
1978	Venera 11	USSR	376	-18 to -21	11.2	Sphere	2.4	138-167	4.35
1978	Venera 12	USSR	379	-18 to -21	11.2	Sphere	2.4	138-167	4.35
1981	Venera 13	USSR	387	-18 to -21	11.2	Sphere	2.4	138-167	4.35
1981	Venera 14	USSR	387	-18 to -21	11.2	Sphere	2.4	138-167	4.35
1984	Vega 1	USSR	412	-18.23	10.7	Sphere	2.4	130	3.06
1984	Vega 2	USSR	412	-19.08	10.8	Sphere	2.4	139	3.29

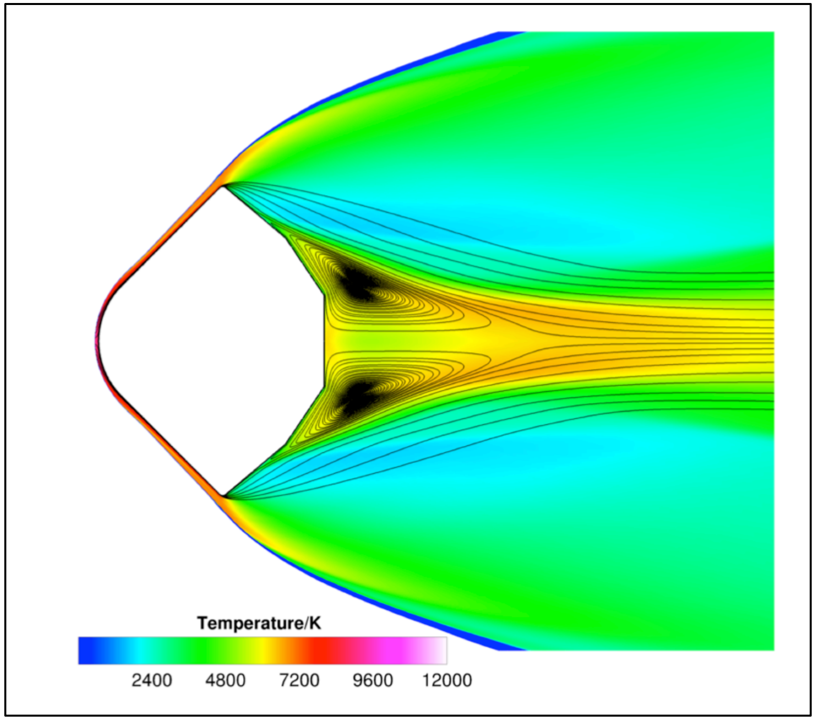
[i] Entry velocities have been defined for a 200 km atmospheric interface at Venus
[ii] Trajectories were simulated from entry conditions and the simulations themselves were based on engineering estimates
[iii] The maximum heat flux is the combination of engineering estimates for cold-wall convective and radiative heat fluxes

Ref: Dutta, S., Smith, B., Prabhu, D., and Venkatapathy, E., "Mission Sizing and Trade Studies for Low Ballistic Coefficient Entry Systems to Venus," 2012 IEEE Aerospace Conference, Big Sky, MT, March 2012.

Dynamic Stability

- Dynamic Stability
  - Flow separation and real gas effects can influence the dynamic stability of an entry system
  - The shape of the after-body, free stream conditions (Mach and Reynolds number) and real-gas effects can influence the dynamic stability.
  - Pioneer-Venus probes(45 deg sphere cone fore-body) were statically very stable and did not experience any dynamic instability

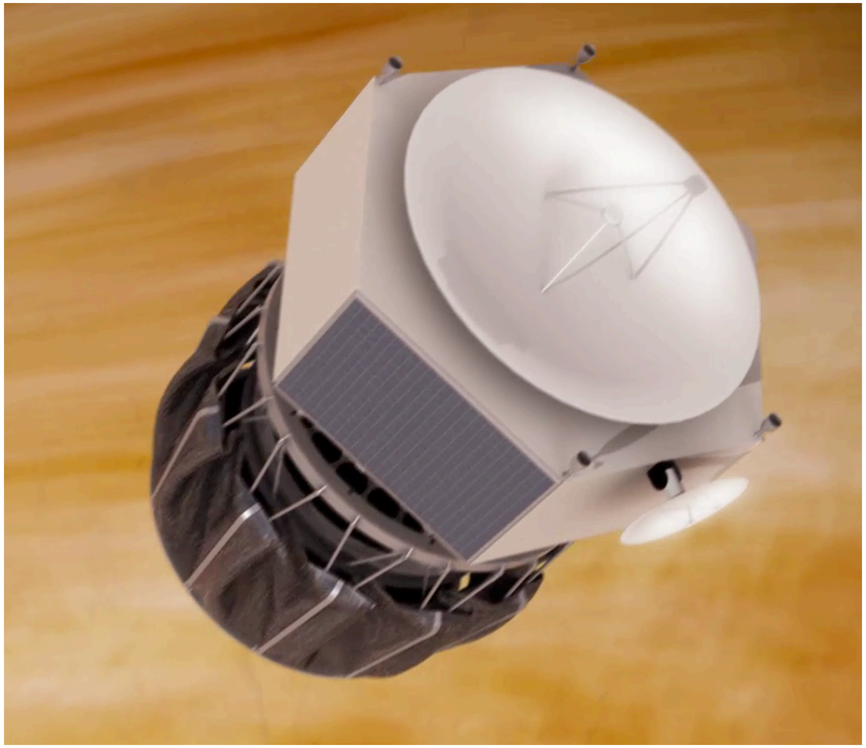


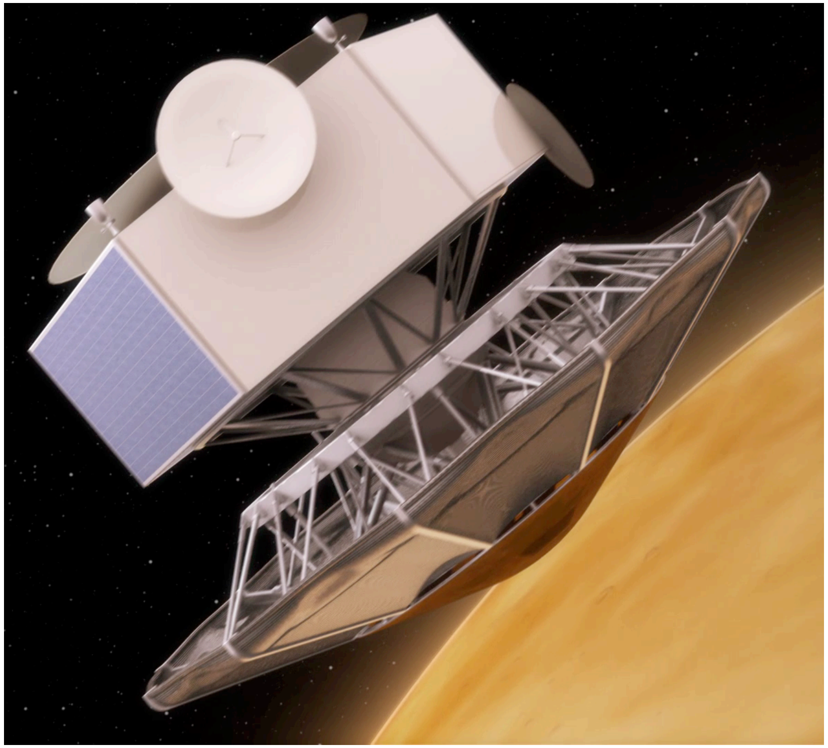


Axisymmetric CFD simulation with flow separation

Entry with Lower Ballistic Coefficient System

- Lower ballistic coefficients were not considered for Venus before 2010
- Potential use of delicate science instruments and fragile power system (ASRG) were precluded due to high entry g'load.
- A mechanically deployable concept called ADEPT, conceived for Human Mars missions, emerged as a potential enabler for achieving low entry g'load by lowering the ballistic coefficient.



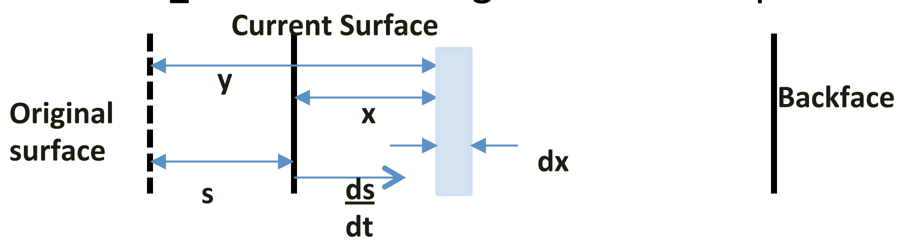


TPS Sizing

1-D In-depth energy balance

$$\rho c_p \frac{\partial T}{\partial \theta}\Bigg)_x = \frac{1}{A}\frac{\partial}{\partial x}\left(kA\frac{\partial}{\partial x}\right)_\theta + (h_g - \bar{h})\frac{\partial \rho}{\partial \theta}\Bigg)_y + \frac{\dot{m}_g}{A}\frac{\partial h_g}{\partial x}\Bigg)_\theta + \dot{s}\rho c_p \frac{\partial T}{\partial x}\Bigg)_\theta$$

1 2 3 4 5



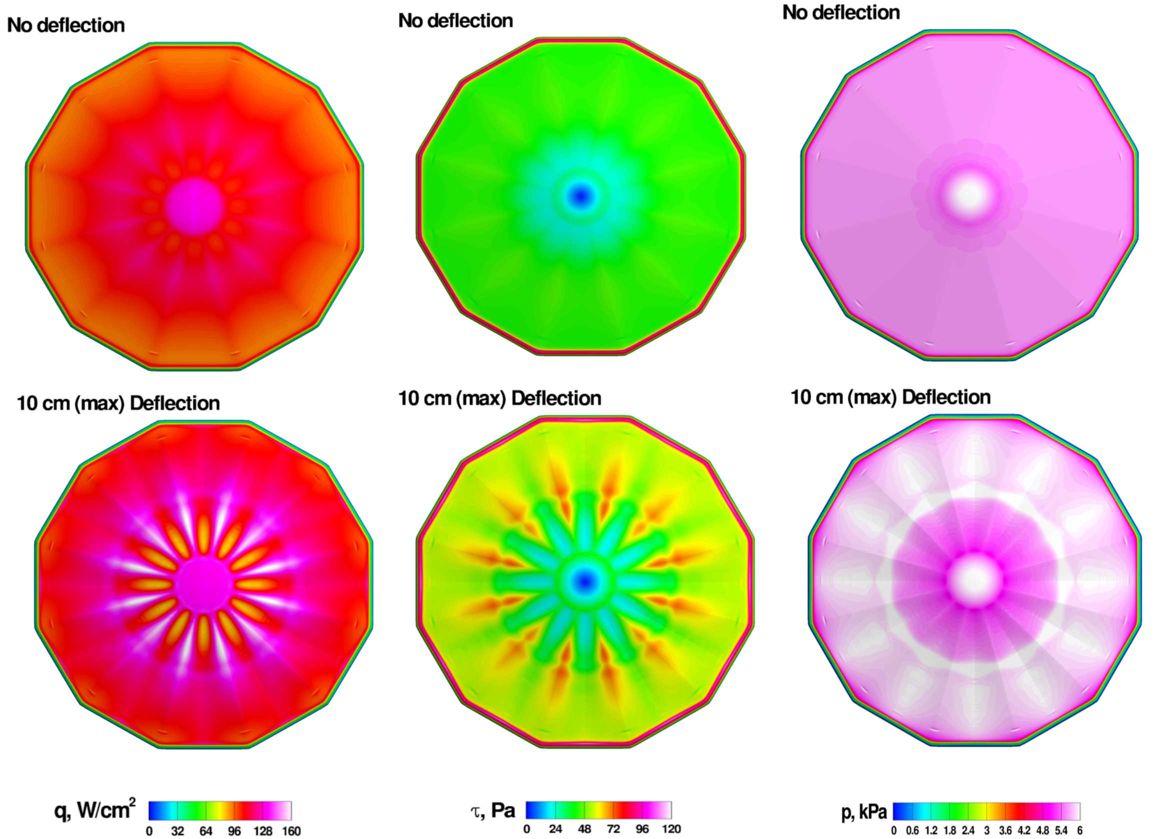
1. Rate of sensible energy storage
2. Rate of thermal conduction
3. Rate of energy due to the conversion of solid to gas (pyrolysis) at a fixed location
4. Rate of convection due to pyrolysis gases flowing through the material
5. Rate of convection of sensible energy due coordinate system movement (coordinate system is tied to the moving surface)

ADEPT-VITaL Aerothermal Analysis

- ADEPT aerothermal environment is complex
  - Cloth permeability causes minor increase in heat flux due to boundary layer suction
  - Rib heating and shear increase with deflection (limited by pre-tension)
  - Local wrinkling could create local cloth hot spots
- Can account for complex aero thermal environment through design margin

Cloth deflection

- Rib heating and shear increase with deflection
- Effect is limited by pretension



Local Wrinkling

- Leads to local cloth “hot spots”
- Increases rib heating and shear