A Multi-Probe Mission at Jupiter is within our Reach!!

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Webb NIRCam composite image of Jupiter
Credit: NASA, ESA, CSA, Jupiter ERS Team; image processing by Judy Schmidt.

Contributions by Mairead Stackpoole, Donald Ellerby, Megan MacDonald, Joe Hartman and Geoffrey Cushman are gratefully acknowledged

Why am I to giving this talk? Who is the target audience?

Motivation:

- *Soon after the Galileo Probe mission, capabilities to manufacture and test heritage carbon-phenolic (HCP) TPS atrophied.*
  - *The capability loss was realized after two decades and impacted Outer Planet, Venus and Mars Sample Return (MSR) missions*
  - *MSR (1997 – 2006) initiated a search and recovery of HCP.*
  - *The Decadal Survey (2003) recommended JPOP* mission (Jupiter Polar Orbiter and Probe)*, but lack of HCP TPS resulted in Juno being proposed without a probe.*
  - *The Decadal Survey (2013) recognized and advised NASA to close the TPS gap.*
- *With community support, NASA initiated a technology development effort to close this gap in 2019 and today, missions to Venus, Saturn, Uranus, and MSR are enabled by new 3-D Woven TPS.*
- *Jupiter, the most demanding mission from an entry and TPS perspective ever, still lacks a viable qualified TPS. While the planetary science community needs to make the case for going back to Jupiter with a probe, this work is an assessment of emerging capabilities to support such a mission when needed.*
- *Recent State-of-the Art (SOA) developments are very promising to close the technology gaps.*

Talk Objectives:

- *Inform/encourage the Science Community about the feasibility of future Jupiter Multi-Probe Missions so they can pursue it*
- *Engage the Entry System/TPS Technology Community as to the emerging capabilities and need to preserve them*
- ***Educate and excite the early career and next generation students interested in future science and technology challenges***

“Chicken or Egg?” The answer : One cannot exist without the Other

Outline

- The Science Rationale for Going Back to Jupiter
  - From Prominent Scientists
- Galileo Probe – A Short Review
  - Capabilities and Expertise that led to its success
  - Post-Galileo – Atrophy
- Advances in the Last Decade
  - Test Capabilities
  - Materials
  - Analysis and Simulation Tools
- Concluding Remarks and Recommendations

Jupiter

- Jupiter has a long history and continues to surprise us!
  - 1610 - Galileo Galilei found the first moons beyond Earth. That discovery changed the way we see the universe.
- Jupiter is the largest planet in the solar system:
  - More than twice as massive as all the other planets combined.
  - Atmosphere is made up mostly of hydrogen (H_2) and Helium (He).
  - Jupiter cannot support life as we know it, but some of Jupiter's moons have oceans beneath their crusts that might support life.
  - A Jovian day is about 10 hours, and a Jovian year is 12 Earth years (to complete one orbit of the Sun).
- In 1979, the Voyager mission discovered Jupiter’s faint ring system.
  - All four giant planets in our solar system have ring systems.
- Nine spacecraft have visited Jupiter.
  - Seven flew by and two have orbited the gas giant.
  - One of the two carried a Probe (Galileo).
  - The other is Juno, the most recent, which arrived at Jupiter in 2016 and has had its mission extended to Sept. 2025.

Why Investigate Jupiter?

- **Theories about solar system formation** all begin with the collapse of a giant cloud of gas and dust, or nebula, most of which formed the infant Sun.
- Like the Sun, Jupiter is mostly hydrogen and helium, so it must have formed early, capturing most of the material left after our star came to be. How this happened, however, is unclear.
- **Did a massive planetary core form first and gravitationally capture all that gas, or did an unstable region collapse inside the nebula, triggering the planet's formation?** Differences between these scenarios are profound.
- Even more importantly, **the composition and role of icy planetesimals,** or small protoplanets, **in planetary formation hangs in the balance – and with them, the origin of Earth and other terrestrial planets.** Icy planetesimals likely were the carriers of materials like water and carbon compounds that are the fundamental building blocks of life.
- Unlike Earth, **Jupiter's giant mass allowed it to hold onto its original composition, providing us with a way of tracing our solar system's history.**

Top 10 Key Science Discoveries – Galileo Orbiter and Probe Mission

1. The descent probe measured atmospheric elements and found that their relative abundances were different than on the Sun, indicating Jupiter's evolution since the planet formed out of the solar nebula.

2. Galileo made a first observation of ammonia clouds in another planet's atmosphere. The atmosphere seems to create ammonia ice particles of material from lower depths, but only in "fresh" clouds.

3. Io's extensive volcanic activity may be 100 times greater than that found on Earth's. The heat and frequency of eruption are reminiscent of early Earth.

4. Io's complex plasma interactions in Io's atmosphere include support for currents and coupling to Jupiter's atmosphere.

5. Evidence supports a theory that liquid oceans exist under Europa's icy surface.

6. Ganymede is the first satellite known to possess a magnetic field.

7. Galileo magnetic data provide evidence that Europa, Ganymede and Callisto have a liquid-saltwater layer.

8. Europa, Ganymede, and Callisto all provide evidence of a thin atmospheric layer known as a 'surface-bound exosphere'.

9. Jupiter's ring system is formed by dust kicked up as interplanetary meteoroids smash into the planet's four small inner moons. The outermost ring is actually two rings, one embedded with the other.

10. Galileo was the first spacecraft to dwell in a giant planet magnetosphere long enough to identify its global structure and to investigate its dynamics.

From: https://solarsystem.nasa.gov/missions/galileo/overview/

Juno Mission Top Science Discoveries

- With its suite of science instruments, Juno has investigated
  - the existence of a solid planetary core,
  - mapped Jupiter's intense magnetic field,
  - measured the amount of water and ammonia in the deep atmosphere, and
  - observed the planet's auroras.
- Juno's observations are helping
  - to determine the global structure and motions of the planet's atmosphere below the cloud tops,
  - mapping variations in the atmosphere's composition, temperature, clouds, and patterns of movement down to unprecedented depths.
- Our view of Jupiter's atmosphere and interior has changed
  - Revealing an atmospheric weather layer that extends far beyond its clouds
  - A deep interior with a diluted, or "fuzzy", heavy element core.

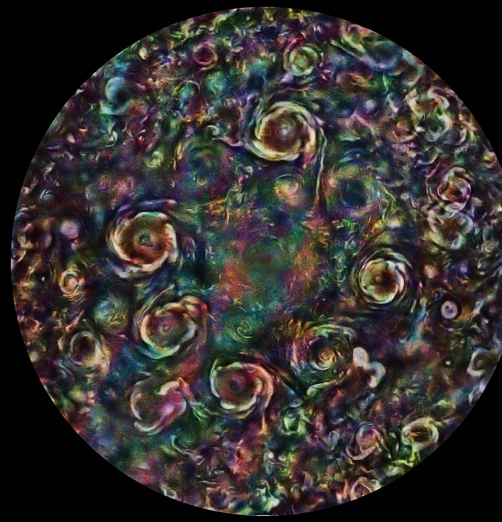
Credits for all pictures: NASA/JPL-Caltech



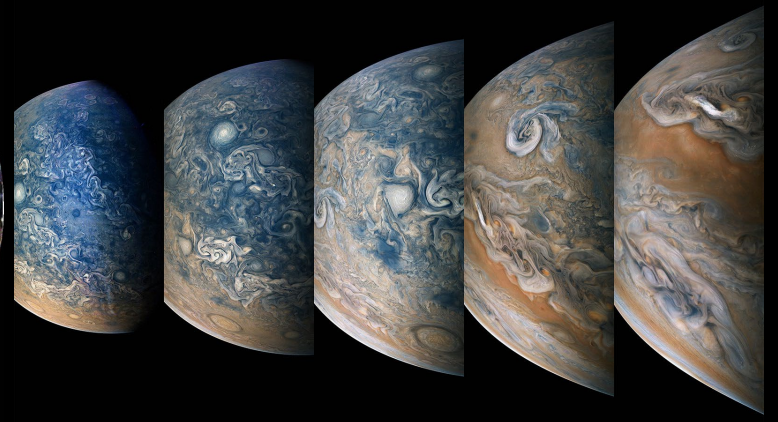
Artist concept of Juno



Jupiter in Ganymede's Shadow



Cyclones at Jupiter's North Pole (false Color image)



Time-lapse Sequence of Jupiter's North

https://www.nasa.gov/mission_pages/juno/overview/index.html

So, why go back to Jupiter?

Recommendation made by prominent scientists in 2006

In the Proceedings, International Planetary Probe Workshop, IPPW-3, ESA SP-WPP263, 2006.

" MULTIPROBE EXPLORATION OF THE GIANT PLANETS – SHALLOW PROBES"

Sushil K. Atreya, Tobias C. Owen, Scott J. Bolton, Tristan Guillot

The following extracted from the concluding remarks section:

"A Jupiter multiprobe mission should be considered after data from Juno, especially on water, have been received and analyzed, as the Juno results will be valuable to the design of a multiprobe mission to Jupiter"

Rationale:

- *Multiple probes to the giant planets are critical for collecting the data required for understanding the formation of our solar system, and by extension, extrasolar systems. Shallow probes deployed to only approximately 10 bars, combined with microwave radiometry from the spacecraft is ideally suited to collect the critical composition data, including water, at Saturn and Jupiter.*

Recommendations:

- *Technology readiness and feasibility studies are also required, and they should be carried out hand in hand with further modeling studies*
- *An investment in enabling technology, especially (a) the thermal protection system (TPS, or heat shield), …needed.*

Prominent Planetary Scientists Perspectives – Sushil Artreya

Subject: [EXTERNAL] Re: Jupiter Probe - Your thoughts and Science Rationale
Date: Monday, February 20, 2023 at 2:51:20 PM Pacific Standard Time
From: Sushil Atreya
To: Venkatapathy
CC: Atreya, Sushi

Hi Raj--

The biggest science drive
entry probes can do tho

Juno provides a global m
do. However, it does not
metallicity of the planet
would the temperature
of +/-5 K at 1 bar but +/-
equator.

Finally, any future probe

Hope this helps.
Sushil

On Sun, Feb 19, 2023 at

> Sushil: I am working o
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> Your response is much
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> Thank you.
>
> Raj.

Hi Raj--

The biggest science driver is the temperature profile, followed by the noble gas isotopic ratios at high precision. Only entry probes can do those measurements.

Juno provides a global map of the distribution of NH3 and H2O to great depths - 100s of bars, which probes cannot do. **However, it does not measure the temperature, which is crucial for constraining the interior models and metallicity of the planet**. The radio occultations planned on Juno will help but it remains to be seen how accurate would the temperature determination would be. Past radio occultations had relatively large error bars on the order of +/-5 K at 1 bar **but +/-1 K is needed. ASI on the Galileo probe did better than that already but only near the equator.**

Finally, any future probe mission needs to be of the multiprobe kind.

Hope this helps.
Sushil



Planetary Scientist

Prominent Planetary Scientists Perspectives – Conor Nixon



Astronomer & Planetary Scientist

Subject: Re: Jupiter Probe
Date: Monday, February 20, 2023 at 6:34:40 PM Pacific Standard Time
From: Nix
To: Ver

Dear Raj,

This is excell

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require a ver

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If you can let

Best regards
Conor

Conor A. Nixo
Research Spa

Associate Lab
Planetary Syst
NASA Goddar
Greenbelt, MD
tel: +1 301 286
fax: +1 301 28

Fron
Date
To: '
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Conc
area
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Dear Raj,

It's a great question – what do we still need to know after Juno? This is not a simple question and would require a very detailed discussion or STM, but let's examine some high-level aspects.

Juno is primarily a remote sensing spacecraft, with the goal of understanding Jupiter's interior structure. It has instruments including long-wavelength, passive microwave radiometry, near-IR spectroscopy, UV spectroscopy, and magnetic field detection. Juno has told us a lot about the interior layers, gravity field and magnetic field of Jupiter, and a little about the composition.

What has Juno not told us? It's impossible without direct sampling of the atmosphere to tell things such as elemental and isotopic composition. The Galileo probe provided some of that information, but failed to answer all the questions. There is a particular problem with Xenon isotopes, which were not well measured, and constrain the formation/evolution scenarios. Another big question is the chromophores, the particles that take on different colors in the zones and belts.

There are more things we could list and take some science questions directly from the Decadal Survey.

Best regards
Conor

Galileo Orbiter and Probe Missions

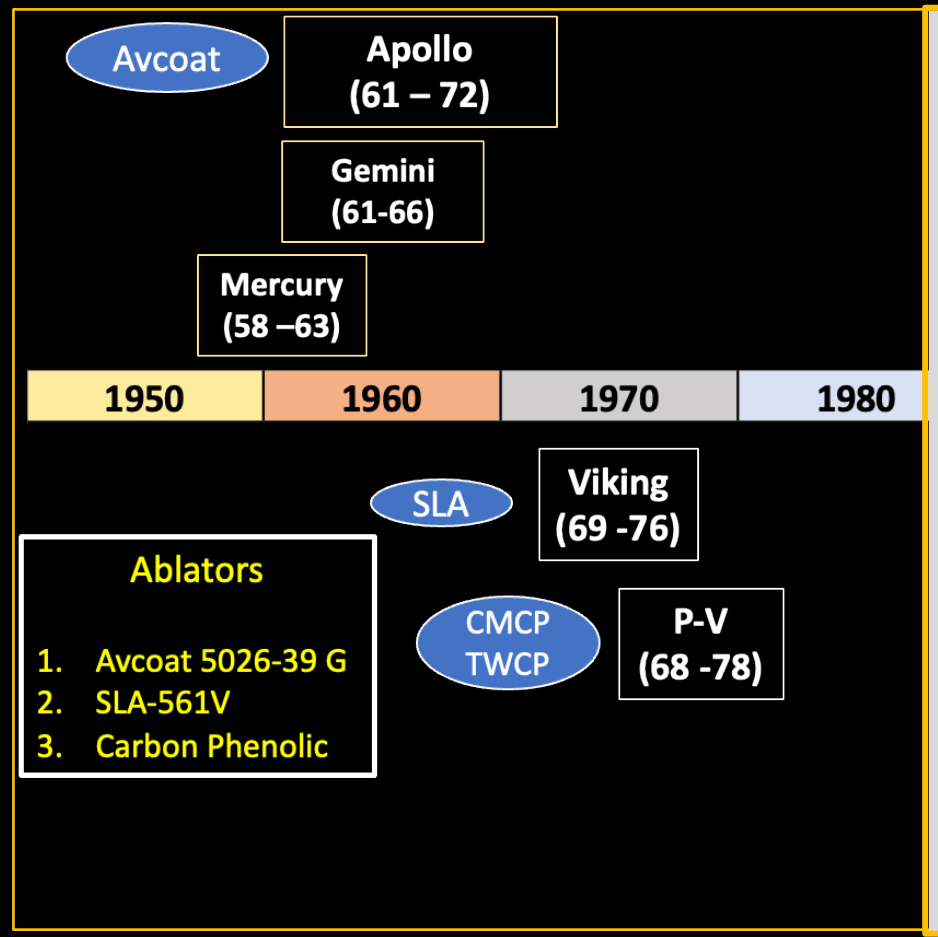
A Short History of NASA Missions including Pioneer-Venus

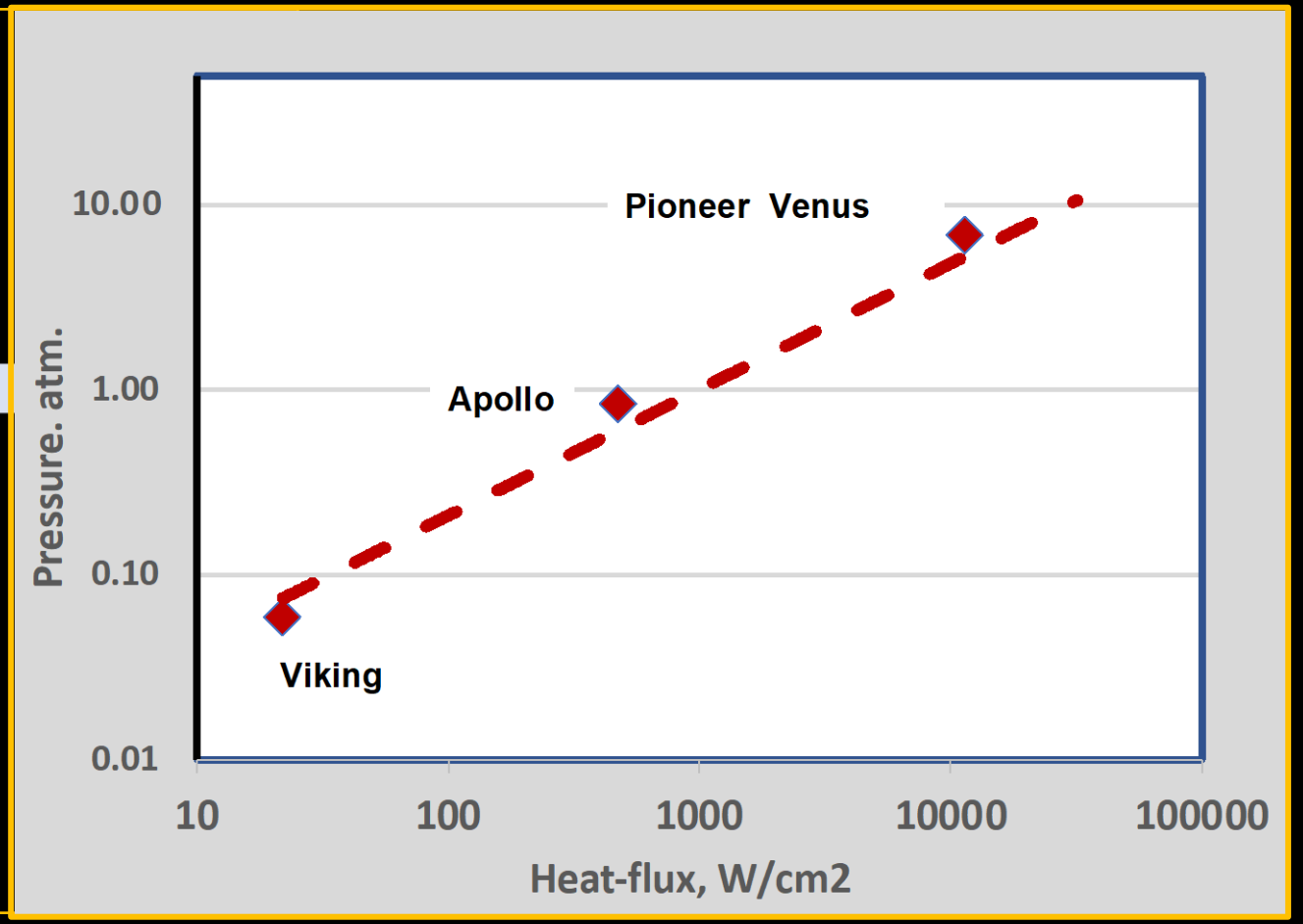
Era of graph papers, slide rules, and human computers

to

Punch-card Programming

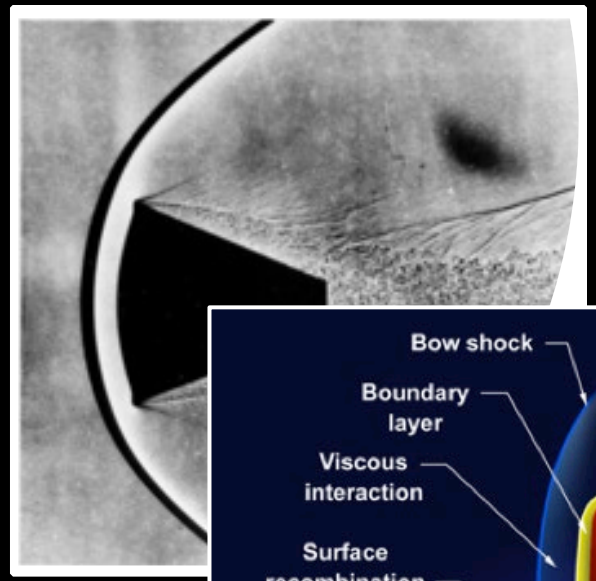
History NASA Missions and Ablative TPS (1950 – 1980):

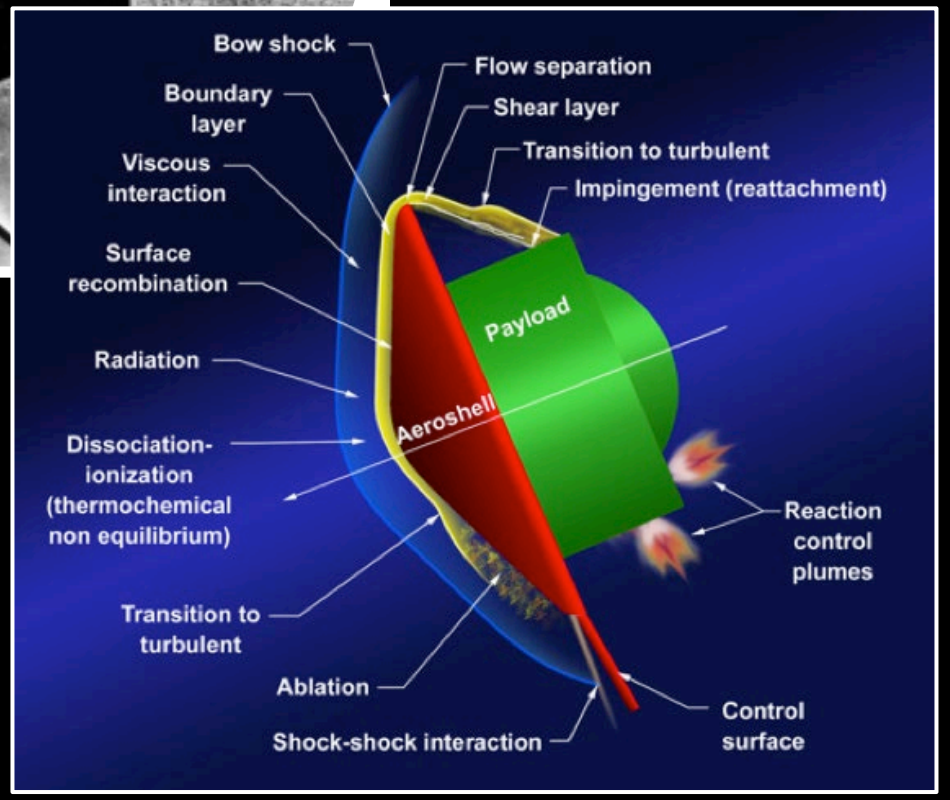




Hypervelocity Flow

FLOW





Images: NASA

- Molecules bunch up against the body and get compressed
- Shock wave forms
- Compression causes heating
- Air-molecules break up into atoms releasing more energy
- At higher velocity, ionization of atoms and molecules leads to radiation from shock-layer
- Temperatures in the shock layer can reach 10,000K – 30,000K
- The TPS material protects the vehicle through mass loss (ablation and pyrolysis)
- As the spacecraft slows down, heating happens only for a short duration during entry

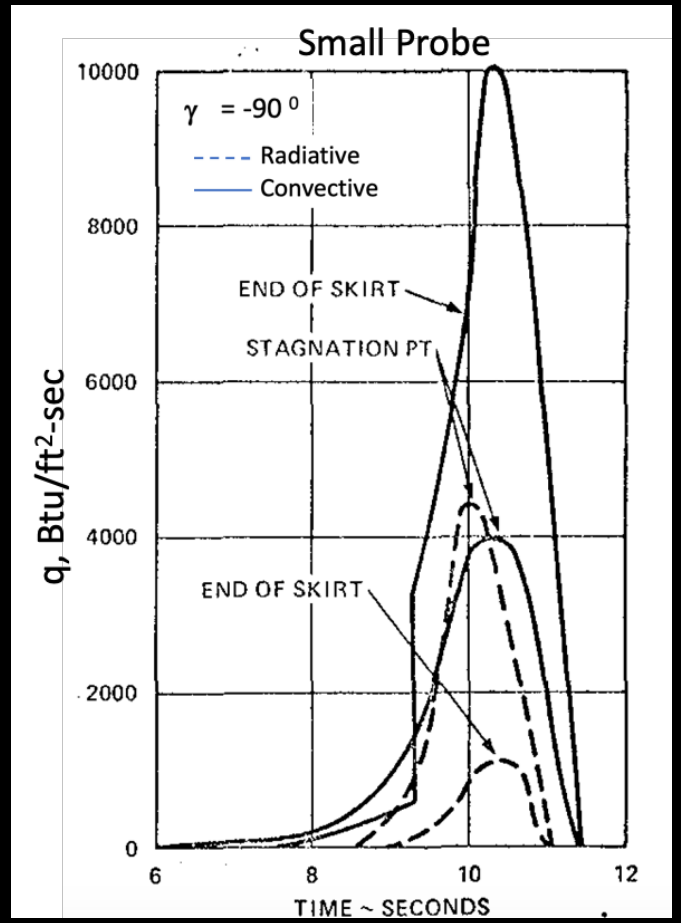
Pioneer-Venus (1978) 3 Small (0.76 m) and 1 Large (1.52 m) Probes
Peak design heat flux 10 kW/cm2 at 10 atm. pressure



NASA

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



Early Pioneering Work on Outer Planet Atmospheric Entry Probe: Heating Environment

Tauber, M., and Wakefield R. M., "Heating Environment and Protection during Jupiter Entry," J. Spacecraft, June 1971

"Ballistic entries into Jupiter …may be feasible over the entire range of entry angles for posigrade equatorial entries with heat-shield mass fractions of the order of 0.45 of the mass at entry. "

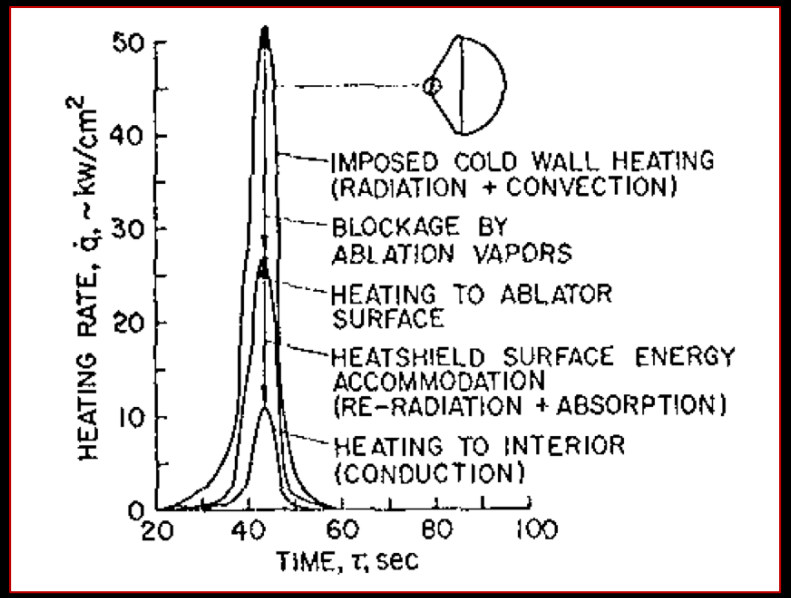
Vojvodich, N., R. Reynolds, T. Grant, and P. Nachtsheim. "Outer planet atmospheric entry probes-an overview of technology readiness." In Conference on the Exploration of the Outer Planets, p. 1147. 1975

" An early Phase A conceptual design study and subsequent follow-on investigations …a common entry-probe system design has evolved over the past three years. The results of this intense effort have clearly demonstrated the suitability of such a system for performing near-term (1979-1983) exploratory in situ investigations of the outer planets Saturn, Uranus, and with suitable modifications, Jupiter.

Table 1 Probe commonality entry environment comparison

Parameter	Saturn	Uranus	Jupiter
Entry speed, km/sec	29	24	49
Entry angle, deg	30	40	7.5
Deceleration - max, -g's	365	264	284
Peak heating rate, kW/cm^2	5	3	40
Heat shield, wt./probe wt.	0.3	0.3	0.5
Total probe weight, kg	100	100	150

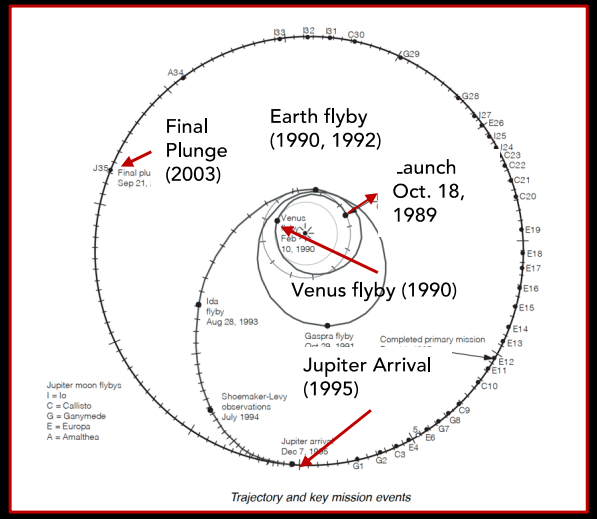
From Ref : Vojvodich, 1975



Stagnation point heating-rate history for Jupiter at -7.5^0 entry angle. (Ref : Vojvodich, 1975)

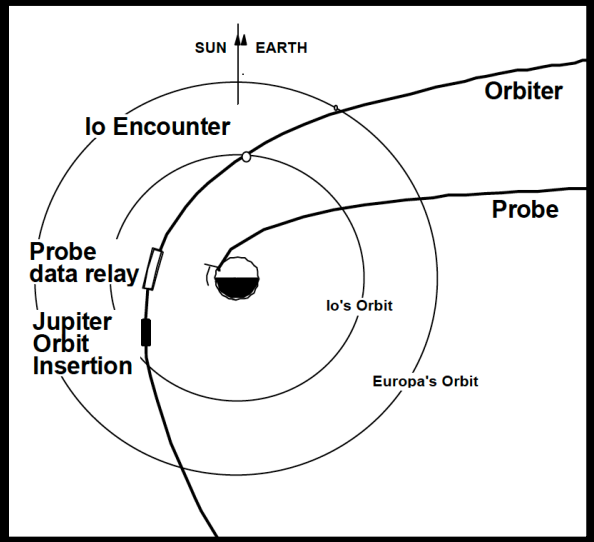
Galileo Mission

- Mission concept early studies (late 1960's – mid 1970's)
  - TPS materials, analysis, and test capabilities
- Jupiter Orbiter and Probe Project approved in 1977
  - Followed the success of Mars Viking (1976) and Pioneer-Venus (1978)
  - Mission was fraught with problems including launch delay from 1985 to 1989
    - Political, budget, redesign and Space Shuttle Challenger accident.
  - Orbiter and a single probe successfully launched on Space Shuttle Atlantis (1989) and arrived at Jupiter (1995)
    - Galileo saved fuel by getting E-V-E gravity assist and visited Ida on its way
    - The probe was released on July 13, 1995, 5 months prior to arrival at Jupiter
- Spacecraft Science instruments:
  - Solid-state imaging camera, near-infrared mapping spectrometer, ultraviolet spectrometer, photopolarimeter radiometer, magnetometer, energetic particles detector, plasma investigation, plasma wave subsystem, dust detector, heavy ion counter
- Atmospheric Probe Science instruments:
  - Atmospheric structure, neutral mass spectrometer, helium abundance, nephelometer, net flux radiometer, lightning/energetic particles, doppler wind experiment



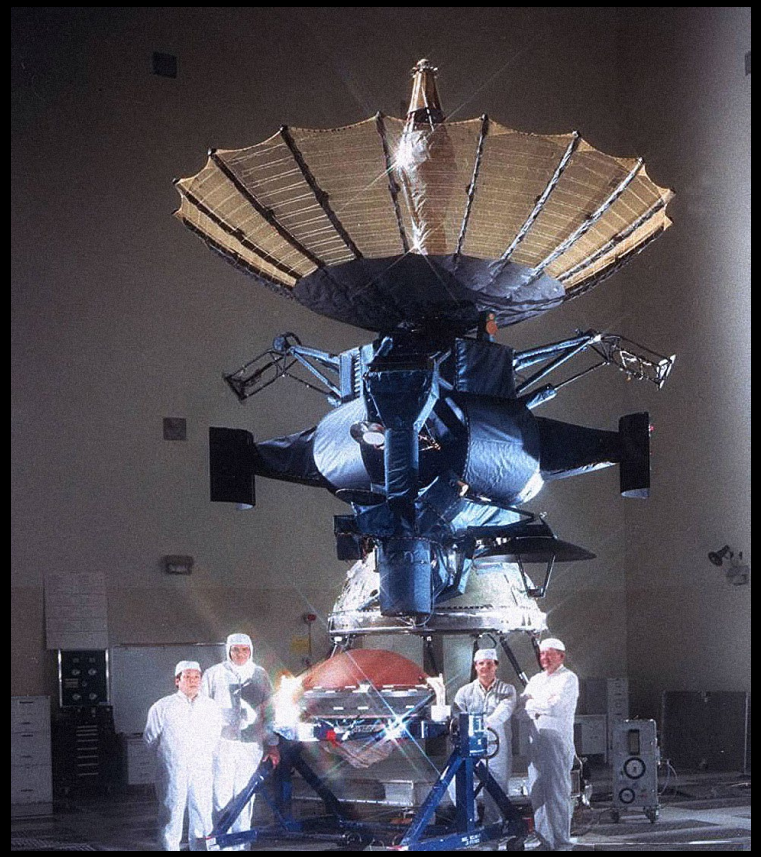
From: Galileo Jupiter Arrival Press Kit

https://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf

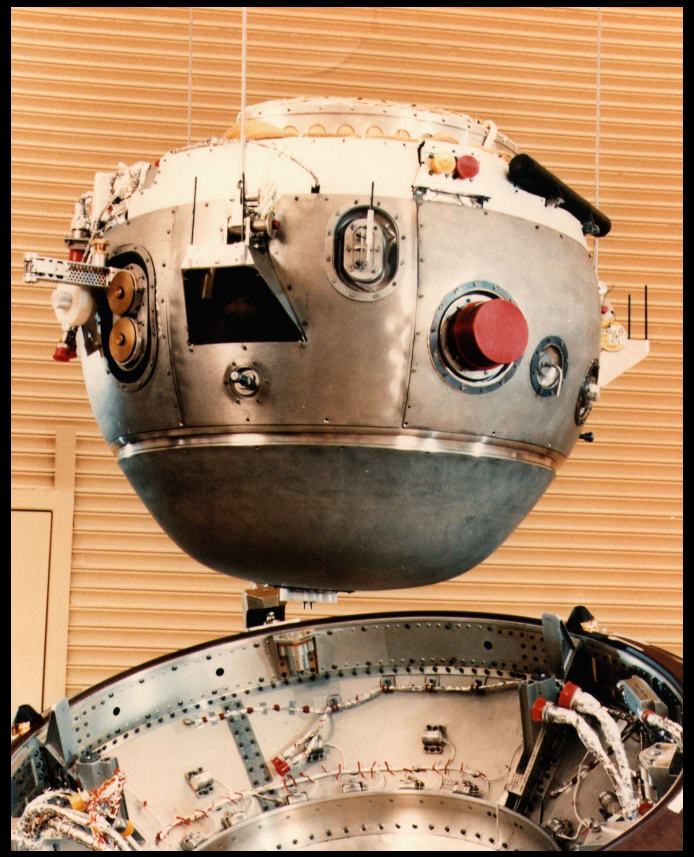


From: Galileo Jupiter Arrival Press Kit

Galileo Orbiter and Probe Mission, first ever at the Outer Planet



NASA/JPL



NASA/JPL

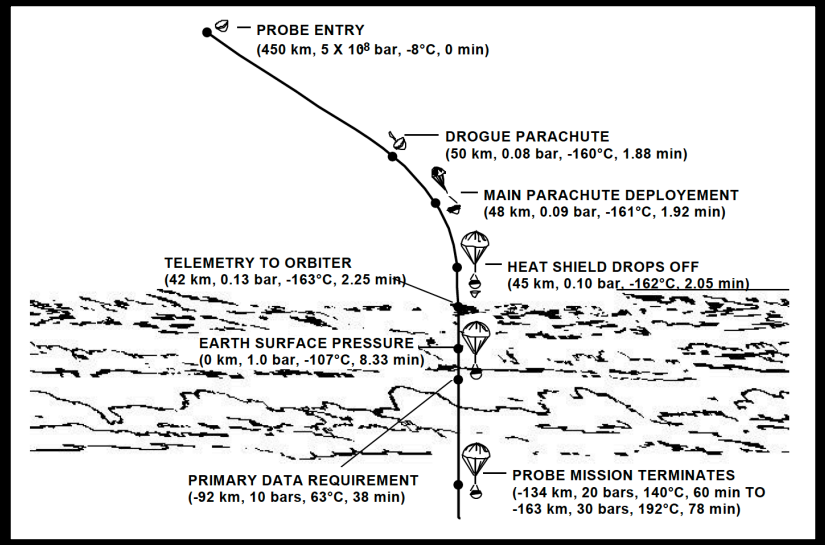


NASA/JPL

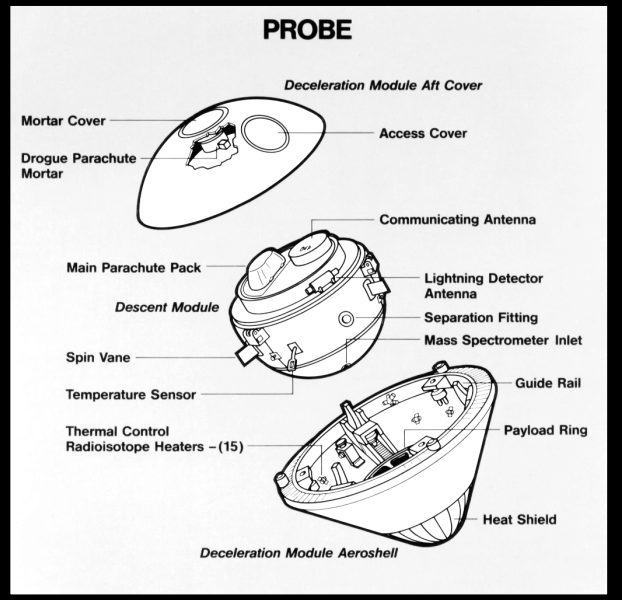
The Probe entry, at ~48 km/s, was the fastest ever and successfully achieved the science goals.

Galileo Probe Entry into Jupiter

- On July 13, 1995, Galileo's descent probe was released and began a five-month freefall toward Jupiter.
- The descent probe, slammed into the Jovian atmosphere at a speed of ~ 48 km/s (106,000 mph) on Dec. 7, 1995.
- The probe slowed by aerodynamic braking for about two minutes, deployed its parachute and dropping a heat shield.
- The science probe floated down about 200 kilometers (125 miles) through the clouds, transmitting data to the orbiter on sunlight and heat flux, pressure, temperature, winds, lightning and atmospheric composition.
- Fifty-eight minutes into its descent, high temperatures silenced the probe's transmitters.
- The probe sent data from a depth with a pressure 23 times that of the average on Earth's surface, more than twice the mission requirement.



https://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf

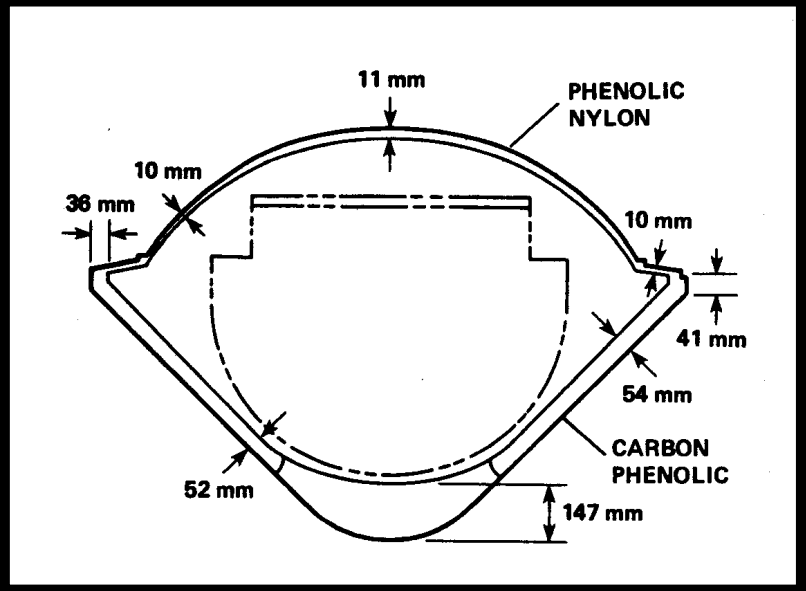


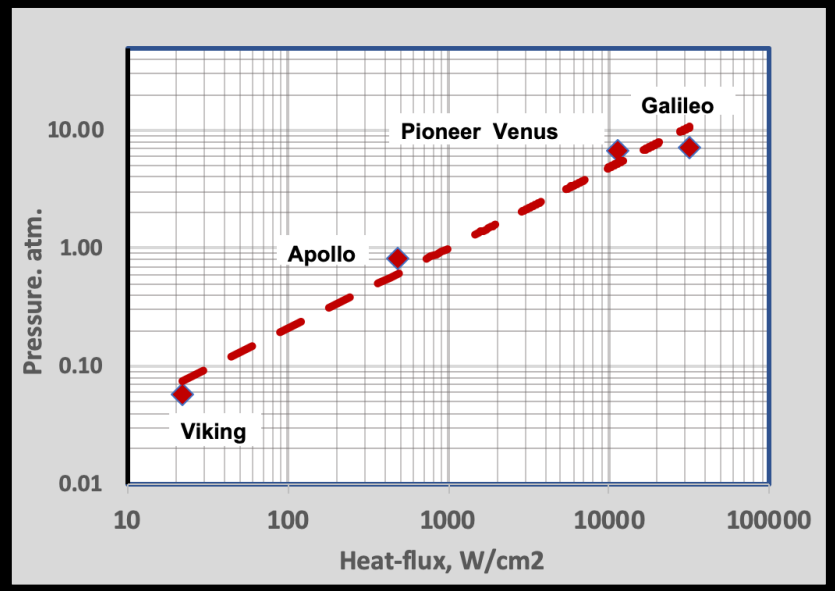
http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/probe_spacecraft.html

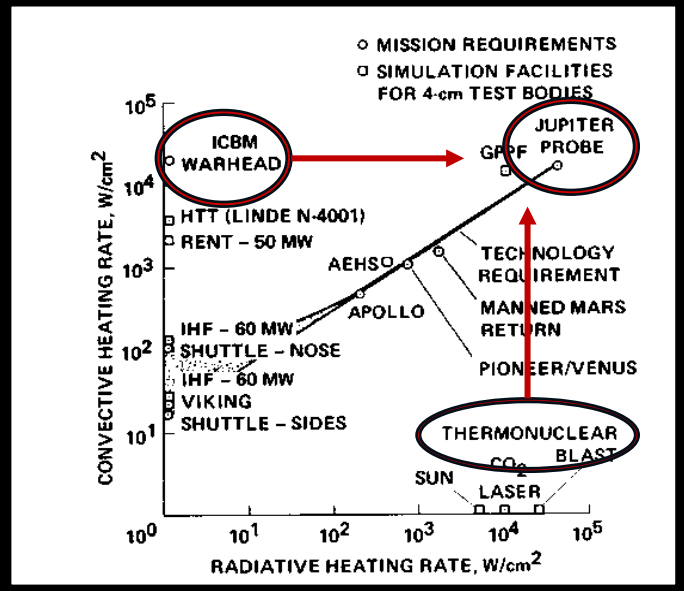
Galileo Entry at 47.4 km/sec:

Stagnation heat-flux and pressure were estimated to be 30,000 W/cm2 and 7.3 atm

- Heatshield made of Carbon Phenolic (2 piece): chop-molded and tape wrapped (Heritage from P-V)
- Heat shield mass was 45% of entry mass by design with 14.7 cm thickness at the stagnation point and 5.4 cm at the flank and shoulder regions in anticipation of massive recession
- Greater than the combined convective heating at the nose tip of a ballistic missile and the radiative heating from a thermonuclear explosion







From: Givens, J., L. Nolte, and L. Pochettino. "Galileo Atmospheric Entry Probe System-Design, development, and test." 21st Aerospace Sciences Meeting. 1983.

Howe, J., W. Pitts, and J. Lundell. "Survey of the supporting research and technology for the thermal protection of the galileo probe." *16th Thermophysics Conference*. 1981.

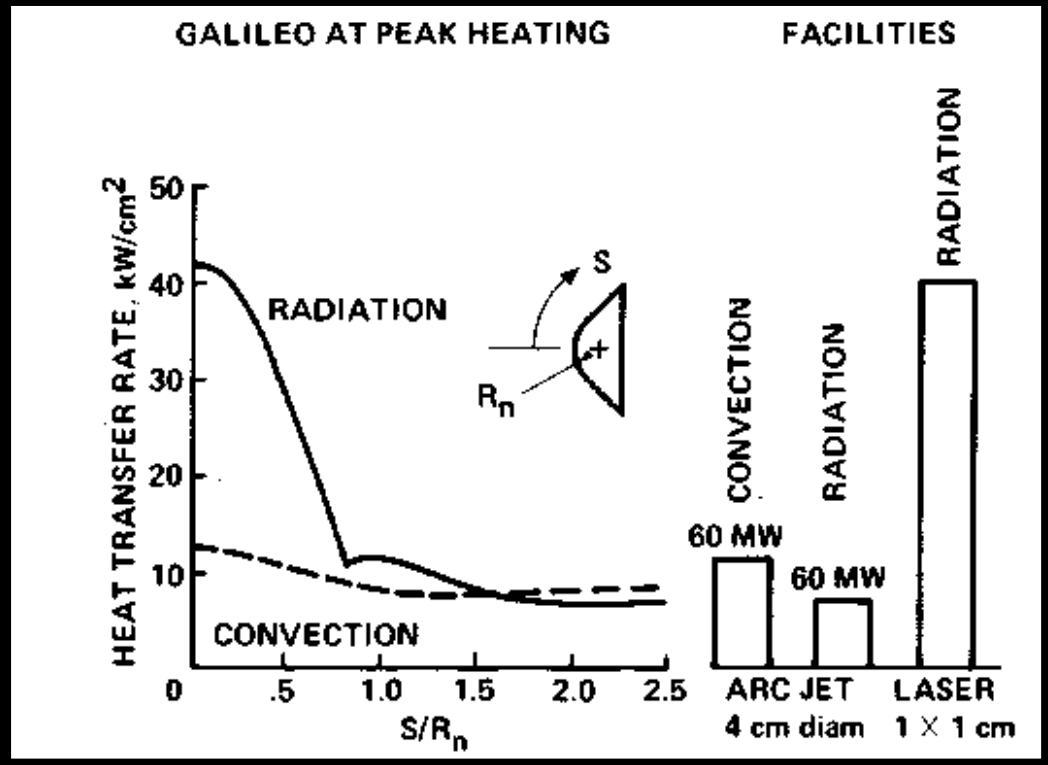
Preparations that led to Galileo Probe Mission Success?

Technology Development that led to the success of Galileo Probe Entry

- Mission success requires:
  - Technology, Manufacturing and Integration Readiness (TRL, IRL and MRL) sufficiently high to execute the mission with confidence
- Material: Carbon-Phenolic was the TPS of choice for heatshield – No other alternate was available and was successfully flown on P-V. (high IRL and MRL)

But:

  - Jovian atmosphere was not well known
  - Lack of validated hypervelocity entry environment **simulation and analysis prediction tools** for Outer Planets (H_2/He)
  - Mission design including flight **TPS sizing methodology and tools needed confidence**
- TPS Material performance and flight design tools were anchored with newly developed ground tests in support of Galileo probe mission.
  - Giant Planet Facility (H_2/He) and Laser Test Facilities were developed in support of relevant TPS testing
- Only way to gain confidence in analysis tools was to perform code-to-code comparisons.



Howe, J., W. Pitts, and J. Lundell. "Survey of the Supporting Research and Technology for the Thermal Protection of the Galileo Probe." *16th Thermophysics Conference*. 1981.

Simulation and Analysis Tools:

Atmospheric models, Trajectory Design and Heating Predictions

- Trajectories were calculated to include
  - Effects of latitude, azimuthal angle, entry angle, and ballistic coefficient for each candidate probe shape, and to accommodate the fact that Jupiter is a rotating oblate spheroid.
  - Shallow entry in the posigrade direction to take advantage of the velocity of the rotating atmosphere (about 12 km/sec).
- Multiple codes were applied to predict the aerothermal heating and TPS mass loss.
  - RASLE, by W. E. Nicolet (NASA Ames)
  - HYVIS, and COLTS- developed primarily by J. N. Moss, and A. J. Kumar, respectively (NASA LaRC)
  - TOPIC by Brewer and Brant, GE (now LM)

Atmospheric Models

ATMOSPHERIC MODEL	COMPOSITION H_2/H_e (VOL)	
	SP 8069	ORTON
WARM	96/4	100/0
NOMINAL	85/15	89/11
COOL	70/30	78/22

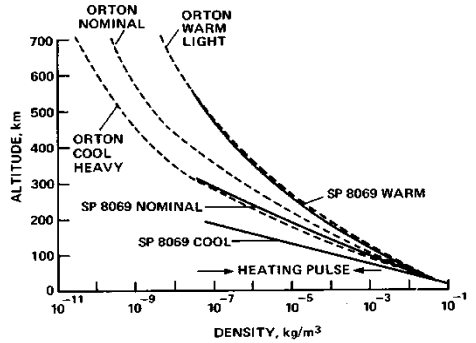


Figure 9-3.– Atmospheric models of Jupiter.

Ref: Howe (1981)

Stag. Heatflux w & w/o mass loss

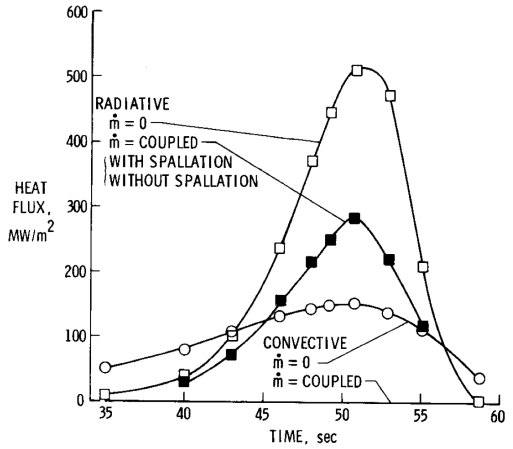
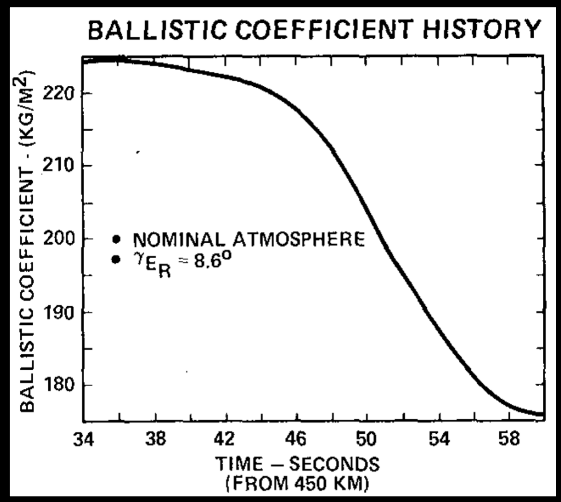


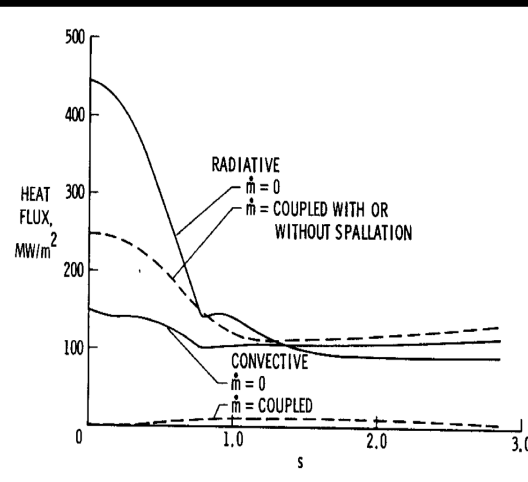
Fig. 16 Stagnation-point heat flux for 335-kg probe.

Ref: Moss (1982)



Ref: Brewer (1980)

Heat-flux distribution

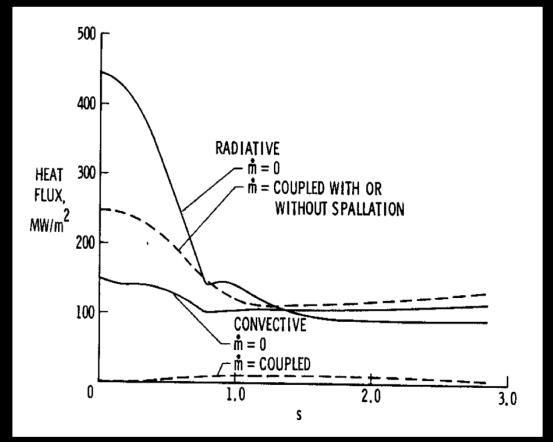


Ref: Moss (1982)

1. Howe, J., W. Pitts, and J. Lundell. "Survey of the supporting research and technology for the thermal protection of the galileo probe." *16th Thermophysics Conference*. 1981.
2. Moss, J., and A. Simmonds. "Galileo probe forebody flowfield predictions during Jupiter entry." *3rd joint thermophysics, fluids, plasma and heat transfer conf. 1982*
3. Balakrishnan, A., and W. Nicolet. "Galileo probe forebody thermal protection-Benchmark heating environment calculations." *16th Thermophysics Conference*. 1981.
4. Brewer, R., and D. Brant. "Thermal protection system for the Galileo mission atmospheric entry probe." *18th Aerospace Sciences Meeting*. 1980.

Simulation and Analysis: Heating Predictions, Mass Loss and TPS Sizing

- The complexity of the flow-physics requires capturing various mechanisms that are unique to entry at ~48 km/s in H_2/He environment.
- Stagnation heating is primarily shock-layer radiation that results in massive ablation, which in turn blocks some of the radiation. The massive ablation pushes the developing boundary layer off the surface. On the flank region, convective heating is small.
- Capturing massive ablation and the radiation blockage were necessary to predict the heating.
- Turbulent transition, spallation were all found to be small.
- The massive mass loss results in lowering the ballistic coefficient which in turn impacts the trajectory.
- Significant recession around the nose makes it blunter and this in turn impacts the mass-loss both in time as well as spatial.



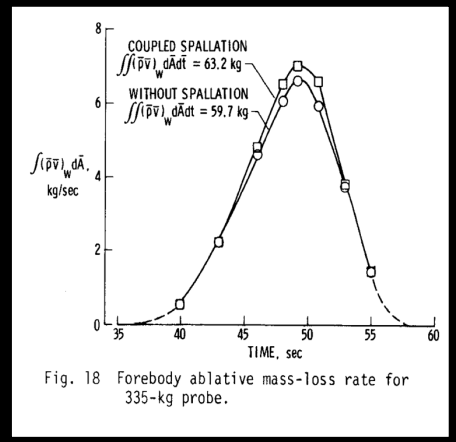


Fig. 18 Forebody ablative mass-loss rate for 335-kg probe.

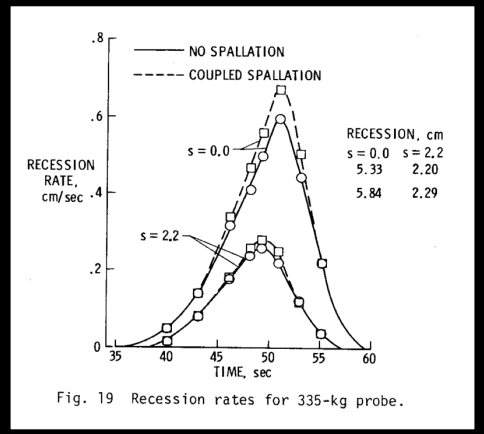


Fig. 19 Recession rates for 335-kg probe.

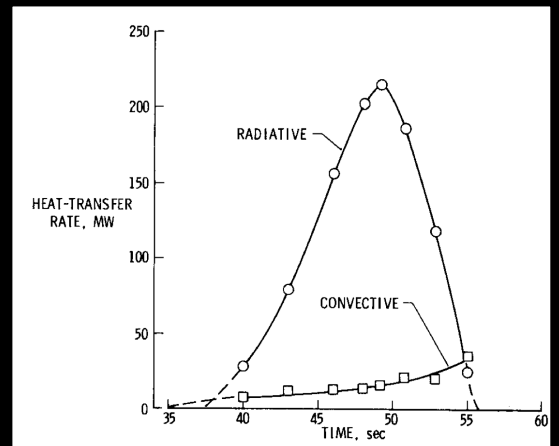


Fig. 17 Forebody heat-transfer rate with coupled injection (335-kg probe).

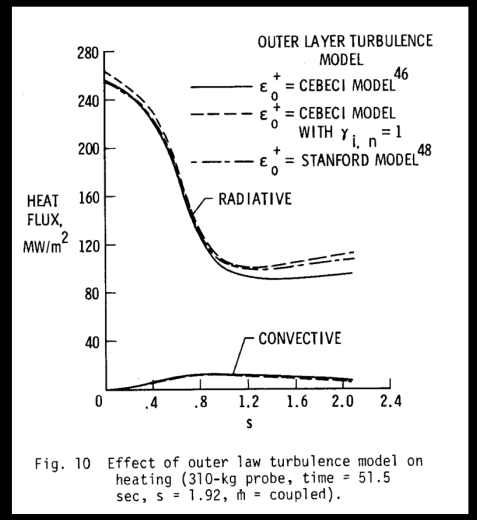


Fig. 10 Effect of outer law turbulence model on heating (310-kg probe, time = 51.5 sec, s = 1.92, ṁ = coupled).

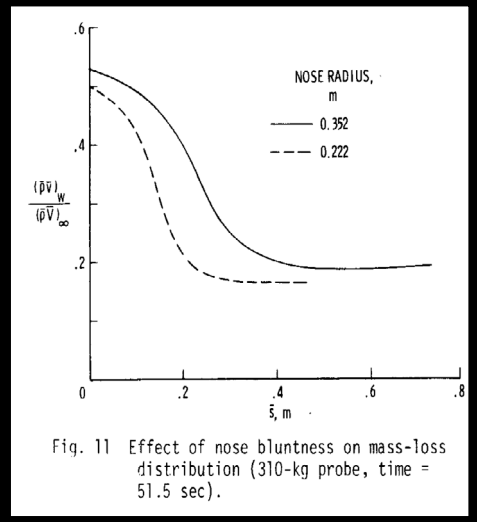


Fig. 11 Effect of nose bluntness on mass-loss distribution (310-kg probe, time = 51.5 sec).

Figures from: Moss, J., and A. Simmonds. "Galileo probe forebody flowfield predictions during Jupiter entry." *3rd joint thermophysics, fluids, plasma and heat transfer conf. 1982*

Test Facility used in support of Galileo Probe TPS Design

- Giant Planet Facility (GPF) 60 MW (H_2/He)
- Laser Test Facility (45 kW CO_2 laser at 10.6 μm)

60 MW

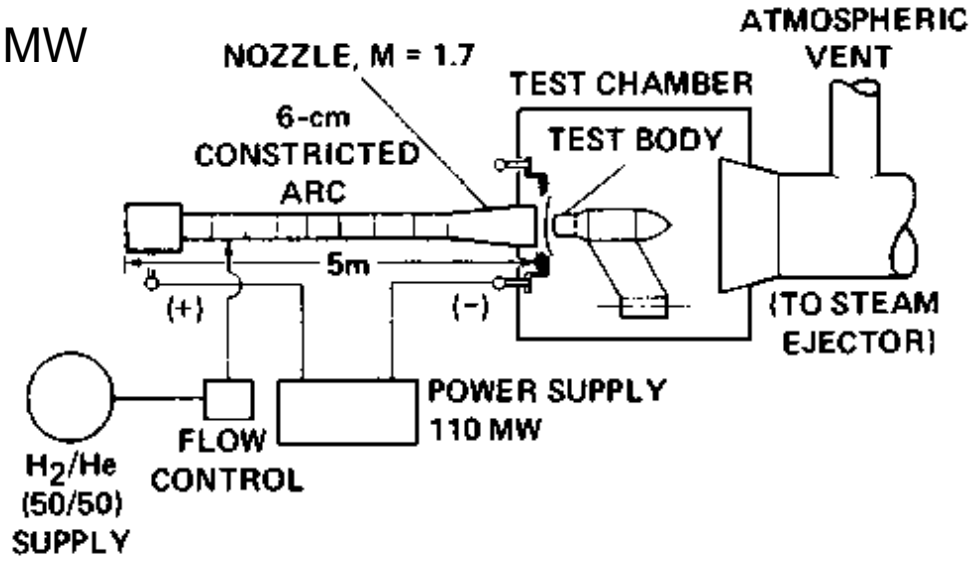


Figure 9-14.– Giant Planet Probe Facility.

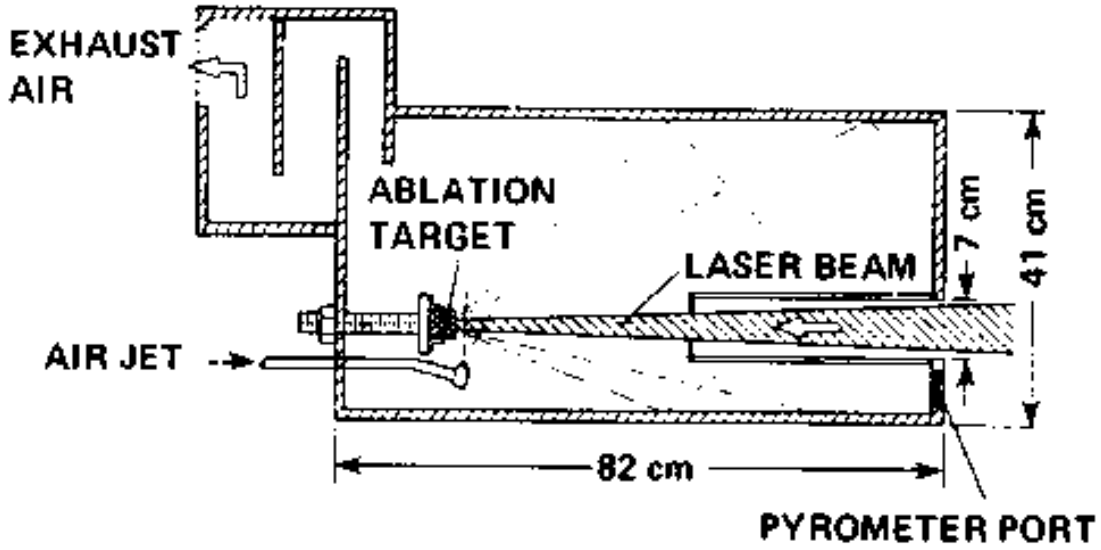


Figure 9-18.– Spallation canister.

Galileo Probe Flight Instrumentation - Recession Measurement

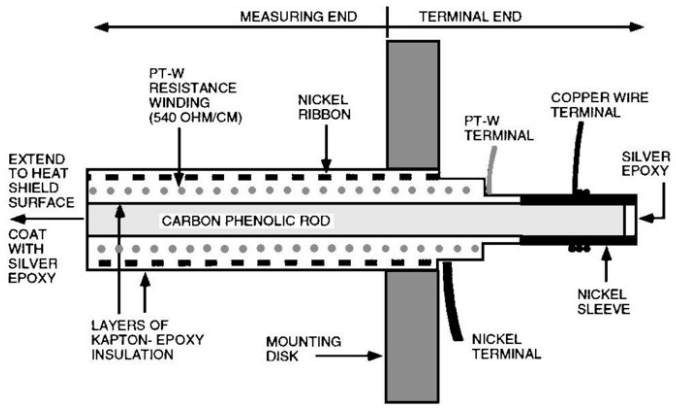
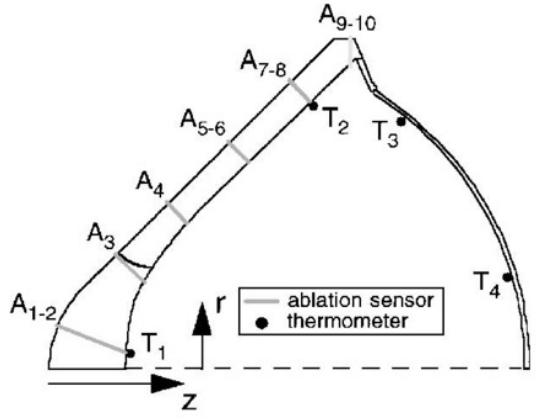
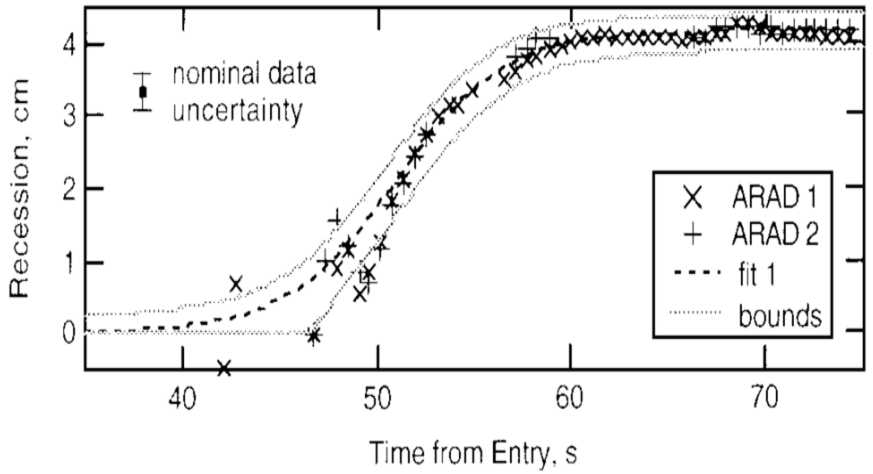


Fig. 4 ARAD.

An ARAD sensor is a three-terminal electrical device that produces a voltage proportional to the length of the sensor.
The char, created by the pyrolysis front, becomes a conductor and hence the length of the non-pyrolysis zone is relatable to the voltage.



g. 2 Illustrated locations of 10 ablation sensors (A_1–A_{10}) ield and four resistance thermometers (T_1–T_4) inside struct rs are not coplanar.



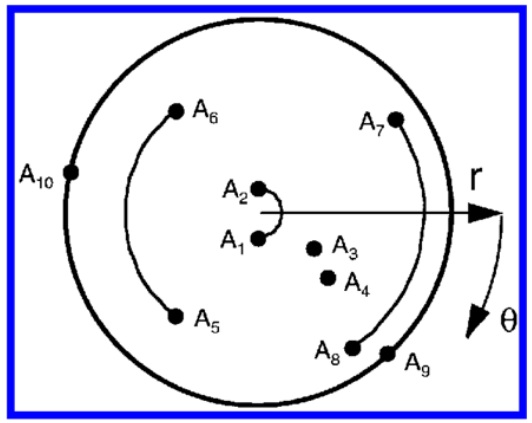
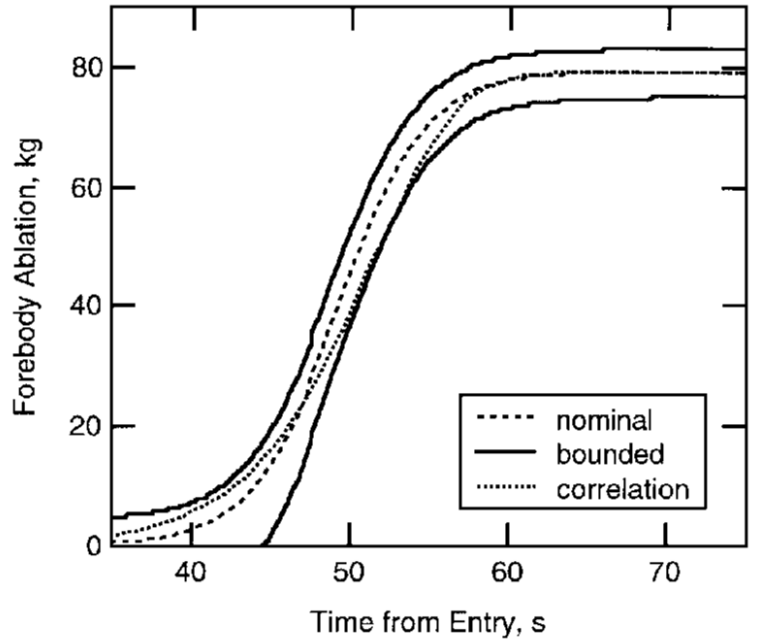
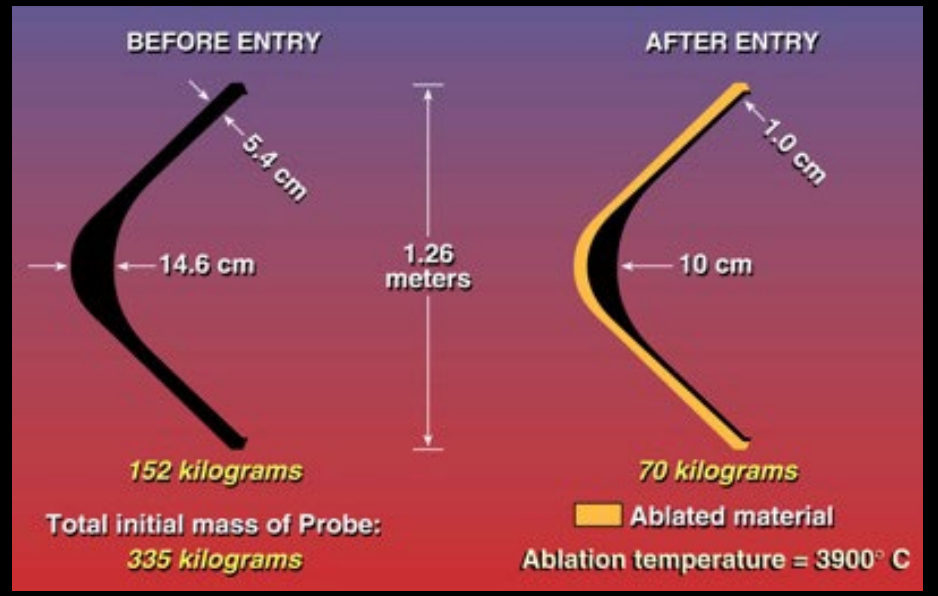


Fig. 3 Radial and circumferential distribution of ARAD sensors; view toward +z direction.



Post-Flight Recession Measurement, What does Tell us?

- Recession was rapid; in about (12 sec) ~ 53% of the heatshield mass loss occurred (~25% of the entry mass ablated away). The overall recession was nearly uniform (~4.5 cm)
- The TPS design tools, analysis capabilities and testing were inadequate even though mission was successful.
  - Over estimated nose heating rates and surface recession
  - Underestimated cone frustum heating rates and surface recession.
- Recessions calculated:
  - GE (now L-M) TOPIC Code: 96% too high at stag. pt., 18% too low on cone.
  - COLTS (LaRC) code: 31% too high at stag. pt., 43% too low on the cone, spallation mass prediction 3.5 Kg.



Lessons Learned

- Codes need modernizing to include better physics and better coupling of heating modes, especially radiation, turbulence and effect of shape change on heating.

Future probe mission will require more TPS mass allocation

- Even for repeating Galileo entry, mass fraction of the TPS will go up considerably from 0.45 to (> 0.6 ?)
- Missions to higher latitude or polar entry would be even more demanding

Post-Galileo Mission – Atrophy of Capabilities and Expertise (1985 – 2010)

- Starting in the 1980s, NASA focused on Space Shuttle Orbiter followed by Space Station at the cost of Planetary missions.
- Expertise in ablative TPS in general was not deemed critical for near term missions
  - Prior to Pathfinder (mid 1990s) there was no planetary mission so to speak
- The Giant Planet Facility and the laser test facilities were allowed to atrophy
  - No missions to Gas Giants were envisioned in the immediate future
  - Expertise was directed to other areas of interest.
- The ability to make heritage (P-V and Galileo) carbon-phenolic also atrophied
  - The specific rayon, the raw material that was tested extensively and qualified by DoD, was no longer manufactured after 1986.
  - The one vendor certified to make chop-molded carbon-phenolic (nose cap of the entry heatshield) moved on to make other products. The process specifications and the expertise slowly vanished.
- In the 1998 – 2002 timeframe when NASA embarked on Mars Sample Return mission planning, we discovered that the ability to make carbon-phenolic heatshield was no longer viable without significant reinvestment
- Science community was interested in a Jupiter Polar Orbiter and Probe mission (~2002), but TPS became the single impediment for proposing JPOP under New Frontiers. Scott Bolton proceeded to propose Juno which has been operational since 2016 and will continue its investigation through 2025

Outline

- The Science Rationale for Back to Jupiter
  - From Prominent Scientists
- Galileo Probe – A Short Review
  - Capabilities and Expertise that led to its success
  - Post-Galileo – Atrophy
- Advances in the Last Decade
  - Analysis and Simulation Tools
  - Test Capabilities
  - Materials
- Concluding Remarks and Recommendations

Recent Developments – Jupiter Multi-Probe Mission is within Our Reach !

We have never been able to “test as we fly” nor have we “flown as we test.”

Galileo Probe mission was NOT an outlier.

Advances, in three key areas, in the past 5+ years are exciting

- Modeling, simulation and analysis capabilities
- New TPS test capabilities
- Newer TPS materials and Heritage Carbon-Phenolic TPS assessment

Galileo-probe TPS recession data can help anchor
simulation and analysis capabilities and “design to fly” future missions with confidence

Recent Advances in Modeling, Simulation and Analysis Capabilities

Advances in modeling, simulation and analysis capabilities

Comprehensive work of Aaron Erb, Tom West, and Chris Johnston is a great achievement.

- *The work is built on 40+ years of knowledge and advances. The detailed modelling to capture the flow-physics interactions and sensitivities outlined are key to future mission design.*

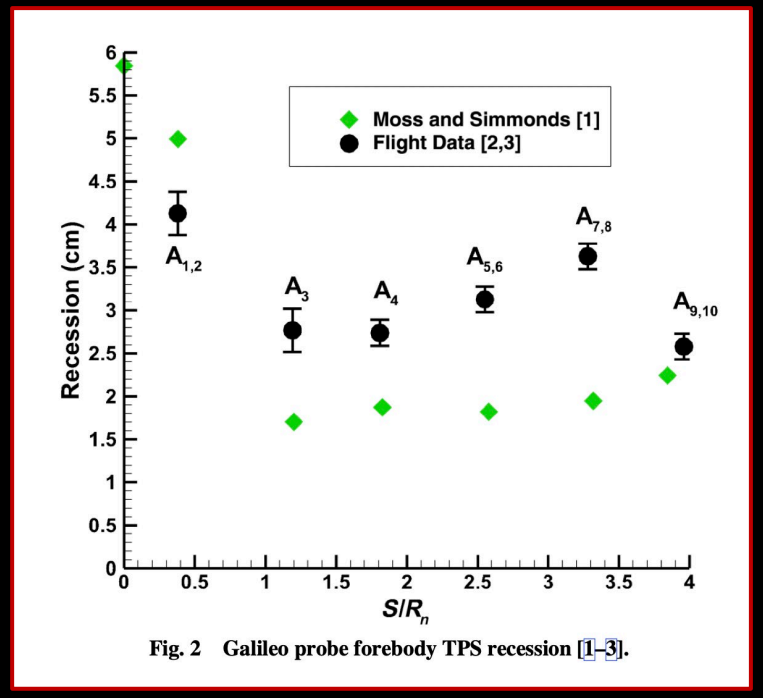


Fig. 2 Galileo probe forebody TPS recession [1–3].

1982

2020

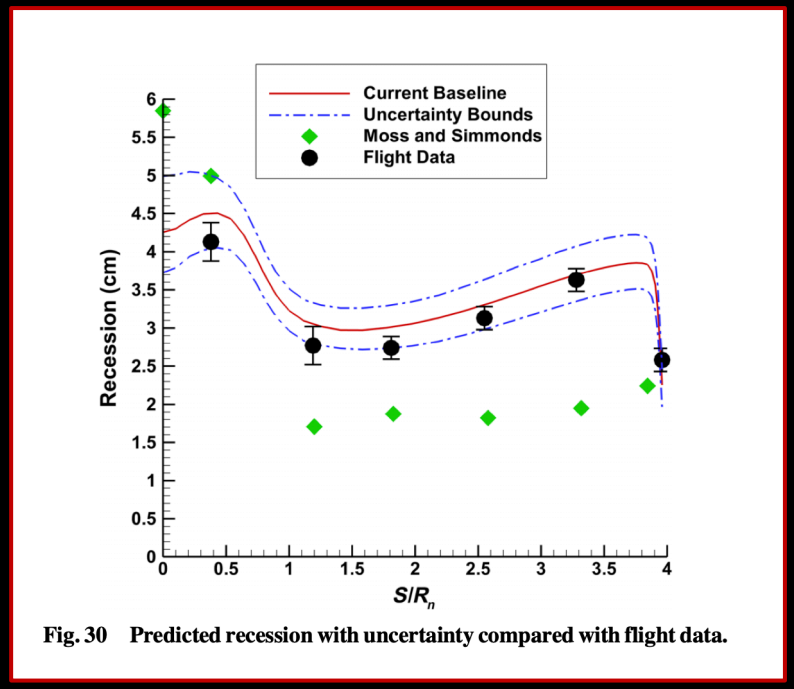


Fig. 30 Predicted recession with uncertainty compared with flight data.

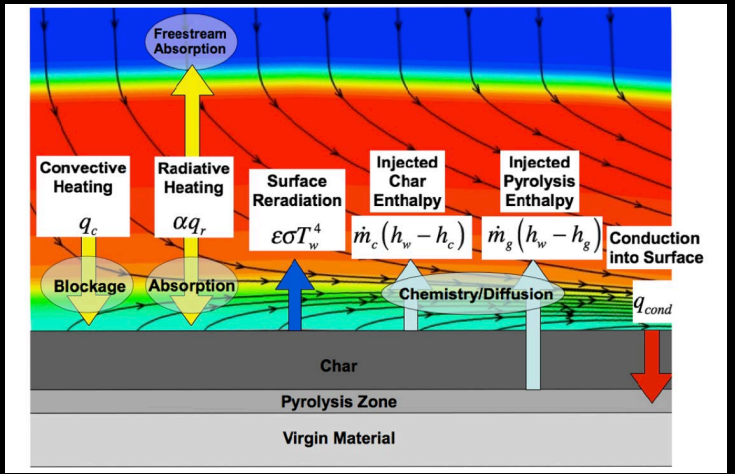
Moss, J. N., and Simmonds, A. L., "Galileo Probe Forebody Flowfield Predictions," AIAA paper 82-0874, 1982. (Fig. from Erb, 2020)

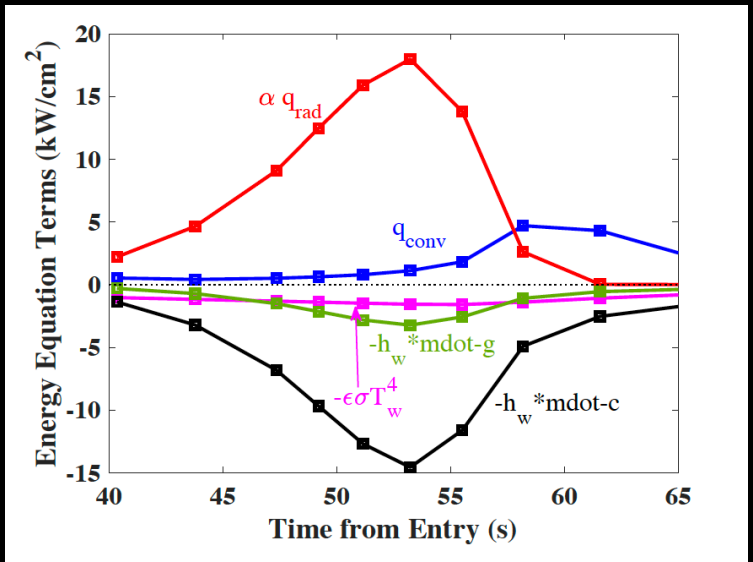
Figure from Aaron J. Erb, Thomas K. West, and Christopher O. Johnston, "Investigation of Galileo Probe Entry Heating with Coupled Radiation and Ablation," Journal of Spacecraft and Rockets, Vol. 57, No. 4, July–August 2020

Importance of the Work by Aaron, Tom, and Chris:

Modeling and Flow-Physics:

1. **Coupled Ablation:** *Capturing the effect of massive blowing and its interaction with boundary and shock layer*
2. **Heatshield Shape Change:** *Blunting of the nose and aerothermal heating impact*
3. **Radiative heating:** *Tangent slab approximation vs ray tracing*
4. **Multicomponent Diffusion**: *Effect of mixing of boundary-layer edge and ablation product species during massive ablation*
5. **Ionization Potential Lowering:** *Effect of electron number density increase resulting in ionization potential for H decrease.*
6. **Coupled Flowfield and Radiation**: *Capturing emission dependency on local conditions and absorption on the incoming radiation from all directions*
7. **Impact of Freestream Radiative Absorption:** ***R****adiative absorption in the freestream, also referred to as the precursor absorption.*





Parametric Uncertainty Analysis:

Uncertainties in physical quantities, such as kinetic rates, lines strengths of atomic species, oscillator strengths of molecular species and heats of formation

Important Assumption:

- *Steady-state ablation*

$$q_{cond} = \dot{m}_c h_c + \dot{m}_g h_g$$

TPS Performance Requirements for Future Jupiter Probe Missions

Ability to model, analyze and predict the recession dominated
Galileo Probe entry at 48.5 km/s gives confidence

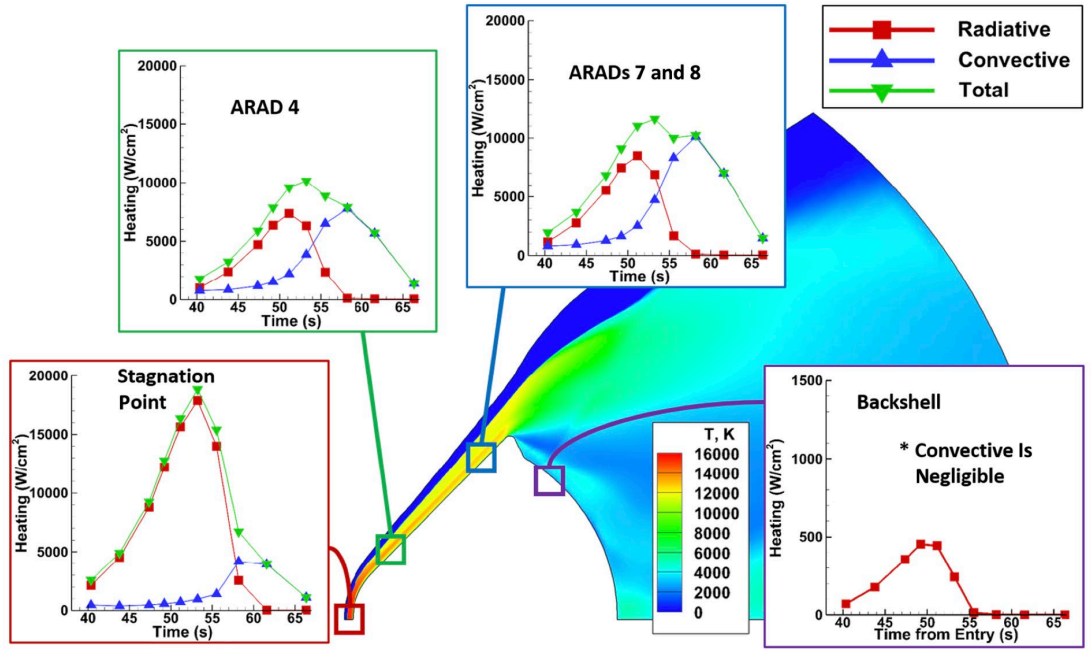
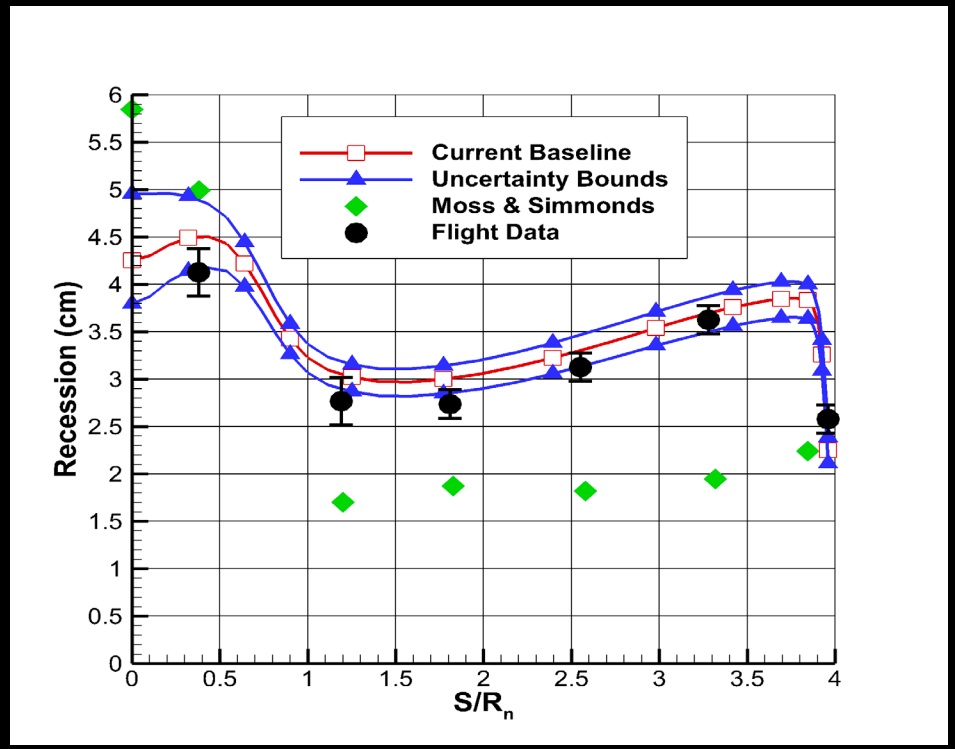


Fig. 3 Baseline heating values with coupled radiation and ablation.



The measured/predicted recession at the conical flank and shoulder regions will demand higher margin, and hence the heatshield mass fraction will be higher for a future Probe mission

Recent Advances in new TPS Test Capabilities

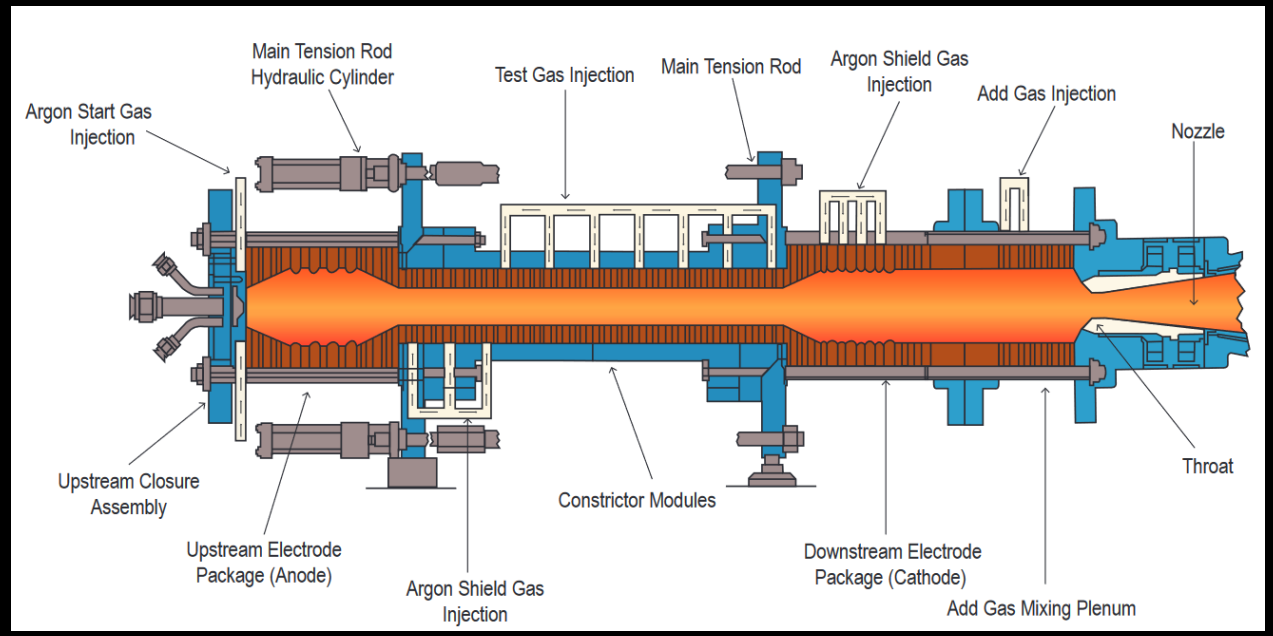
NASA Arc Jet Complex

- 150 MW Interaction Heating Facility (IHF)
- 20 MW Aerodynamic Heating Facility (AHF)
- 10 MW TP3
- 20 MW Panel Test Facility (PTF)
- 20 MW 2x9 Turbulent Flow Duct (TFD)
- Gases
  - Air
  - Nitrogen
  - Oxygen
  - Carbon Dioxide



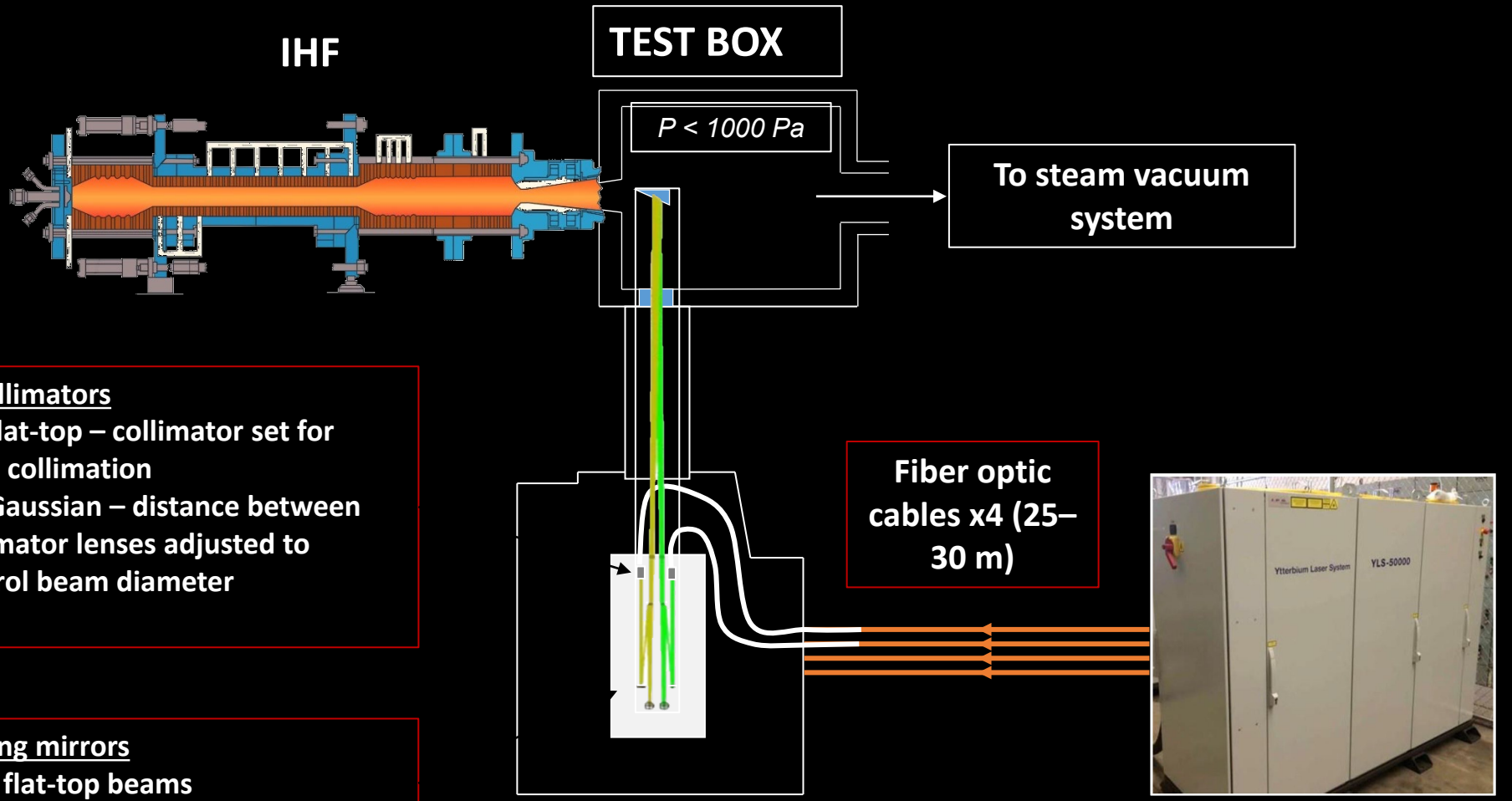
IHF Convective Heating

- The Interaction Heating Facility (IHF) has a 150-MW constricted arc-heater which operates at pressures from 0.1 to 1 MPa and enthalpy levels from 5 to 28 MJ/kg (2000 to 12,000 Btu/lb).
- Can deliver heat fluxes as high as 7.5 kW/cm^2 to stagnation models (7.6-cm nozzle)
- Can operate in stagnation, free jet wedge, or flat panel test configurations in simulated hypersonic boundary layer flow environments
- Laser Enhanced Arc jet Facility (LEAF) is located at IHF



LEAF Addition to IHF

Overhead view (not to scale)



Beam collimators

- For flat-top – collimator set for ideal collimation
- For Gaussian – distance between collimator lenses adjusted to control beam diameter

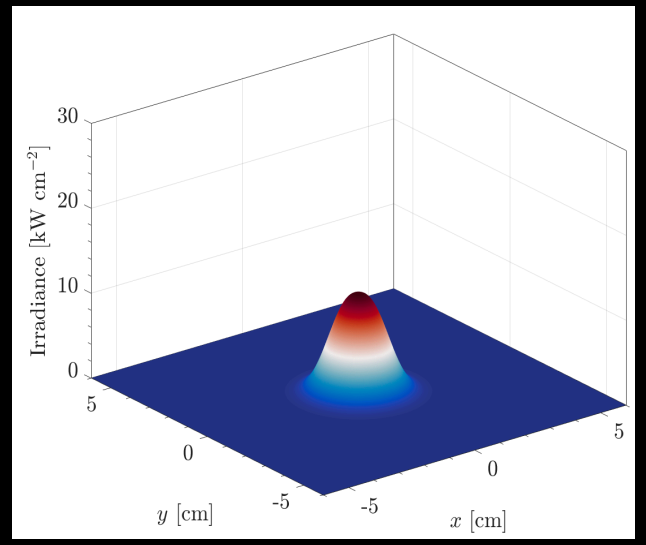
Integrating mirrors

Used for flat-top beams

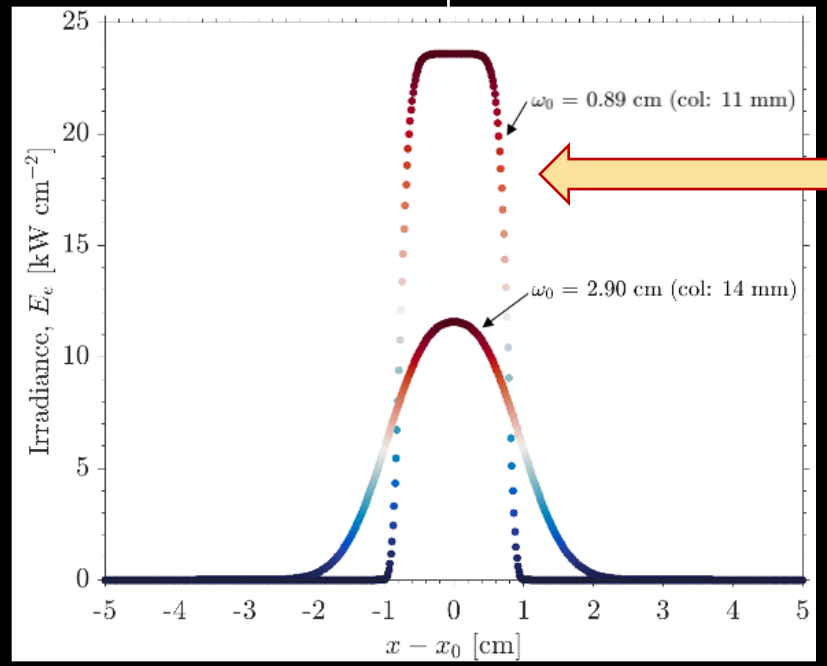
Removed for Gaussian beams

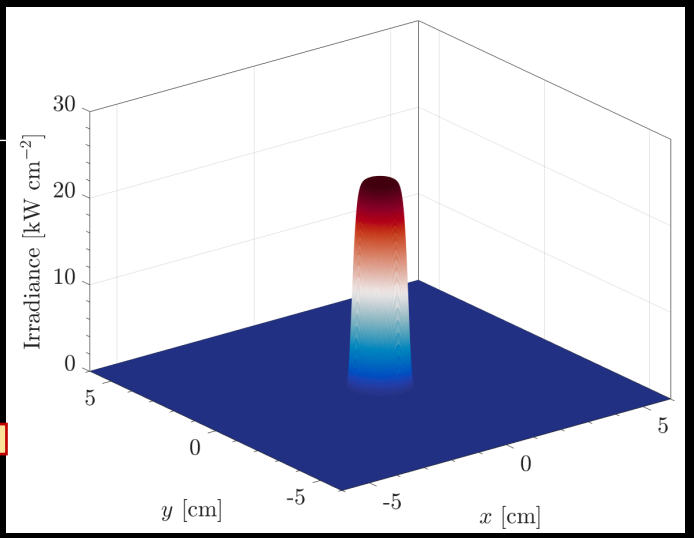
Example Super-Gaussian Fits

for a constant laser power output



50 kW set power





Laser Enhancement System Explained by the Lead Engineer



New & Heritage TPS Materials

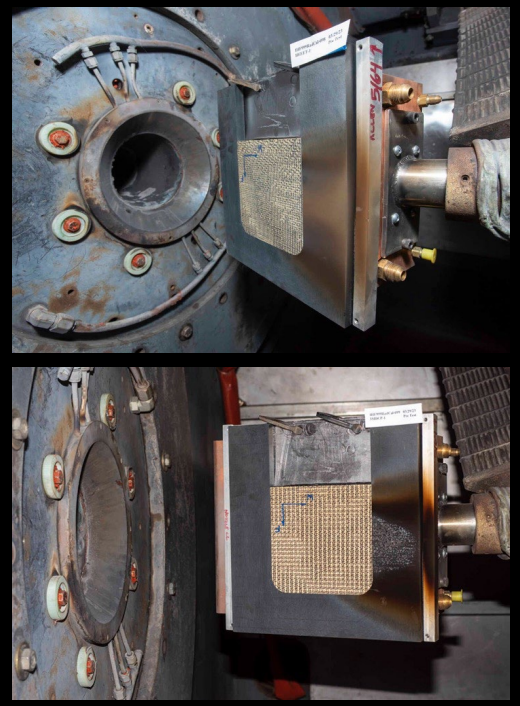
TPS potentially capable of supporting future multi-probe Jupiter mission include:

- **Heritage Carbon-Phenolic** *capability for a small probe could be revived*
  - *NASA secured heritage rayon from stockpile and converted it into carbon fibers (2000 – 2007)*
  - *NASA also recovered all the manufacturing processes for making Chop Molded and Tape Wrapped carbon-phenolic and demonstrated the capability (2005 – 2007)*
- **3-D woven TPS** - NASA funded the development of HEEET (2014 – 2019)
  - *The 2-layer, 3-D Woven HEEET TPS was matured to TRL 6 to enable missions to Venus, faster sample return and outer Planets missions except Jupiter probe mission.*
  - *A variant, a single layer system 3-D woven, is now baselined for MSR Earth Entry System.*
- **3-D Carbon-Carbon**
  - 3-D Woven TPS preform molded and converted into fully dense carbon-carbon.
  - With higher density, 3-D CC is 50% more energy absorbing than carbon-phenolic.
- **Other - 2.5-D C-C variants**

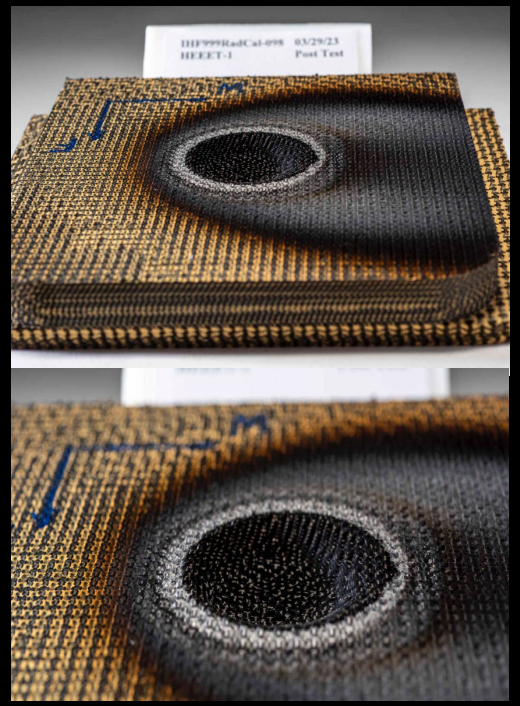
Recent Exploratory Testing using LEAF (Laser)

- Exploratory LEAF testing at 11.6 kW/cm^2 peak irradiance using a single 50 kW laser.
  - Heritage carbon-phenolic, both chop-molded and tape-wrapped, HEEET dual layer and single layer were tested.
- Future plans are to test 3-D carbon-carbon.
- Combined environment testing has been demonstrated.
- With all four lasers, we can achieve heating conditions higher than Galileo entry on a reasonable size wedge test article along with traditional arc jet flow (convective heating)

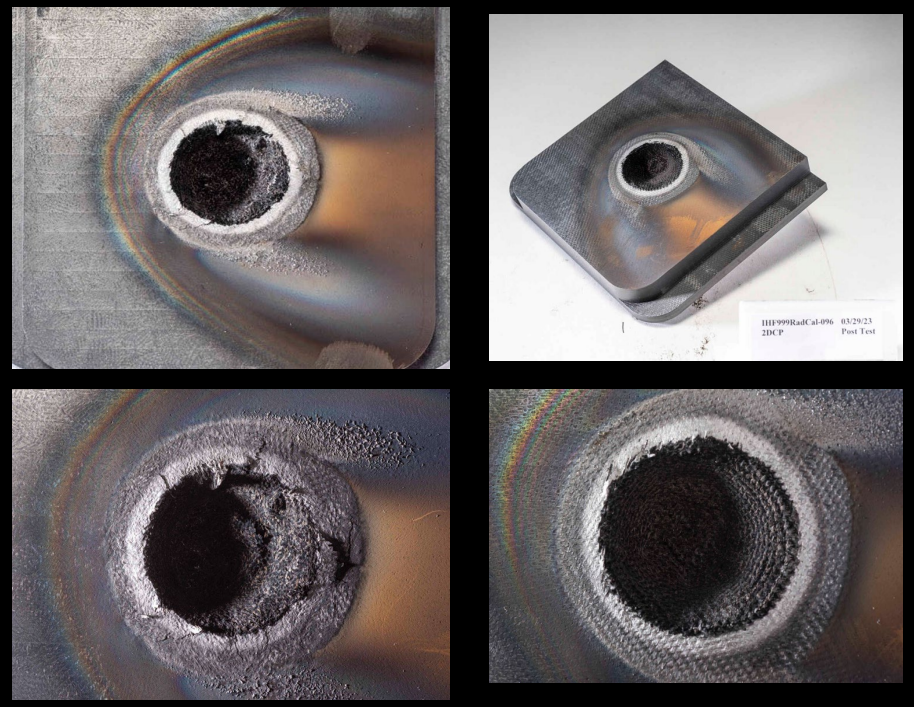
LEAF Wedge Testing



Model Set-up HEEET - Pre-Test



HEEET



Carbon Phenolics (CM & TW)

Jupiter Multi-Probe /Deep Probes Mission Studies

A few mission design and TPS studies were conducted primarily by JPL and NASA Ames (1997 – 2005)

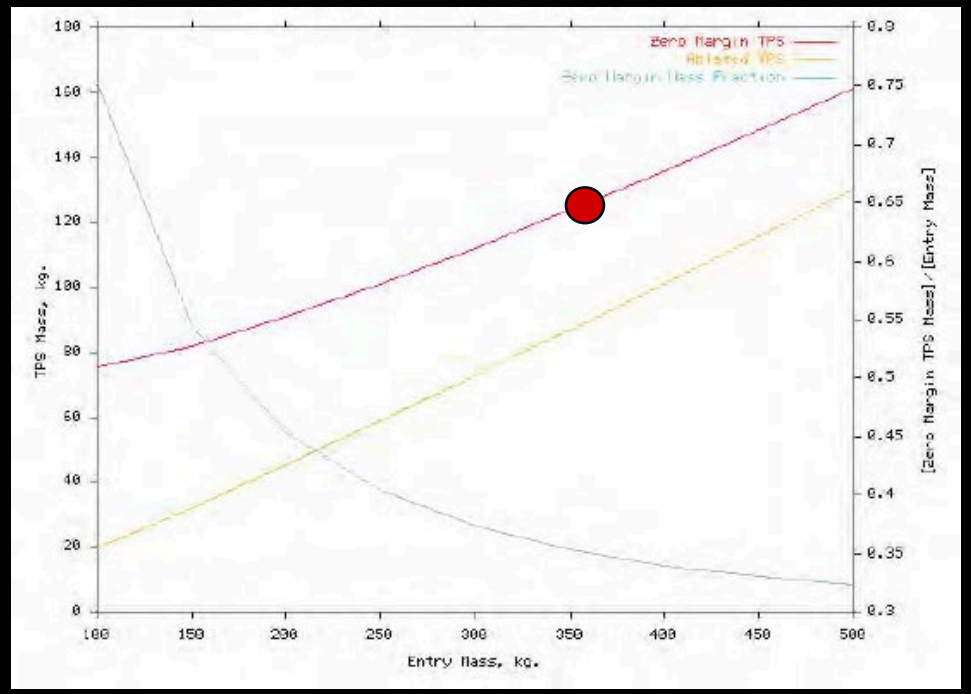
- (2005) Balint, T., “State of Affairs for Jupiter Deep Entry Probes,” 3rd International Planetary Probe Workshop, Greece.
- (2003) Spilker, T., “JIMO Delivery and Support of a Jupiter Deep Entry Probe,” Forum on Concepts and Approaches for Jupiter Icy Moons Orbiter, 2003
- (2002 & 2003) Spilker, T., and Ballint T., “Team-X - Jupiter Deep Multi-Probes Study,” JPL.

The above studies did an assessment of higher latitude entry with 1/2 the size of the Galileo Probe (1/8th volume)

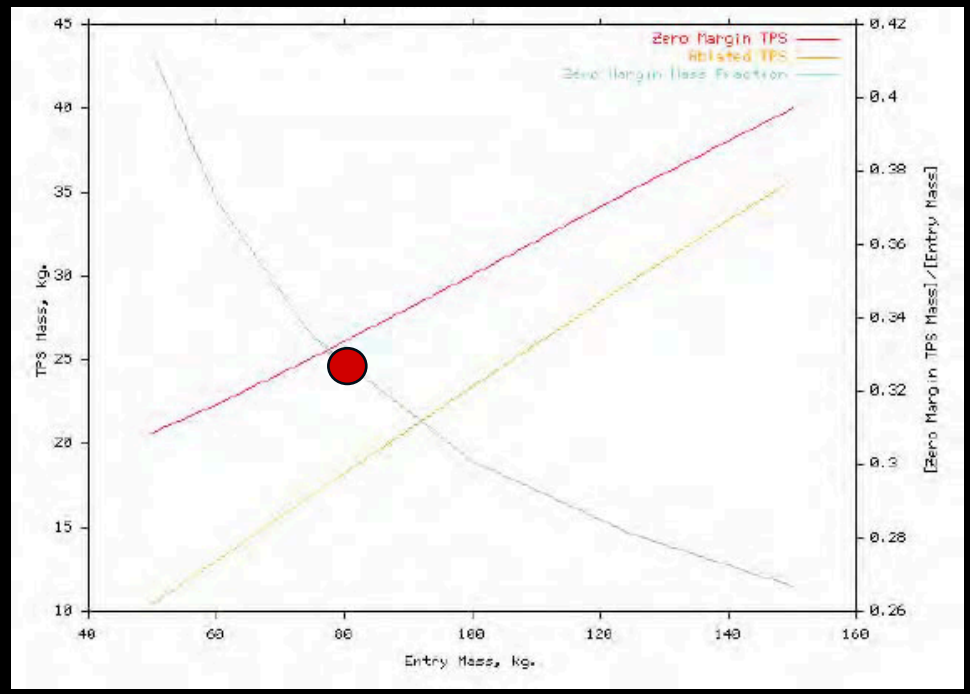
- **The TPS mass fraction reduced by 1/2 (to ~ 35% of the probe mass of 80 kg)**
- These studies did recognize TPS atrophy and advocated for the recovery of Carbon-Phenolic.

Jupiter Deep Probe(s) TPS sizing using Jupiter Atmospheric Entry (JAE) Analysis Code

- JAE Code, a fast preliminary engineering design code is currently the best tool available and provides the best estimates for TPS mass fraction for speeds up to 60 km/s.



JAE Results: Galileo Entry Conditions at Full Scale



JAE Results: Galileo Entry Conditions at Half Scale
(1/8 volume of full-size Galileo Probe)

Above figures from: Wercinski, P., et al., "Jupiter Deep Probe Design - Entry/Descent System Challenges and Trades," IPPW 3, Greece, 2005

Ref: M. Tauber, P. Wercinski, L. Yang and YK Chen, "A Fast Code for Jupiter Atmospheric Entry Analysis", NASA TM 209796, 1999.

Concluding Remarks

- Galileo Orbiter with Probe and Juno missions have achieved great scientific discoveries.
- Two decades ago, lack of TPS capability resulted in Juno to be an Orbiter only mission.
- The Science community needs to make the case for further investigation of Jupiter with higher latitude, multiple probes missions.
- We recognize such a mission will take time and perseverance.
- We have the three key capabilities to consider Jupiter Probes : Analysis, Testing and Materials.
- For the engineering community to help the Science community with the critical TPS capability, we need the mission design community to perform studies to guide the science and technology.
- The EDL community needs to continue the advancement of TPS and EDL systems.
- We, the probe community, need to take steps to avoid atrophy through knowledge and capabilities preservation.
- We must ensure the next generation of scientists, mission designers and engineers are made aware of the possibility and are informed of the past and present capabilities.