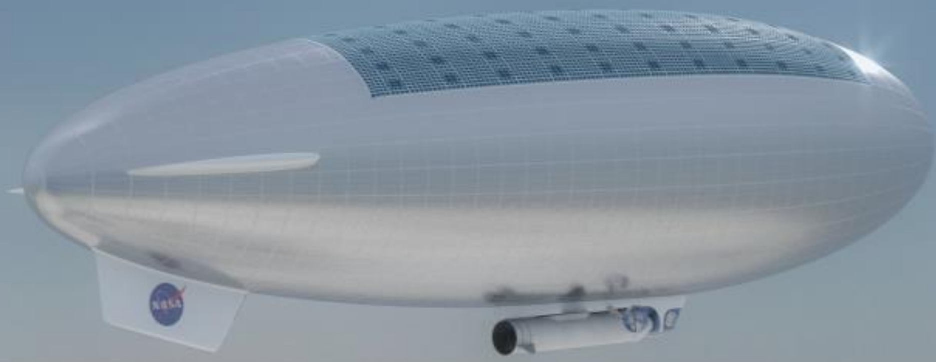
HAVOC:

High Altitude Venus Operational Concept

AIAA SPACE 2015 Conference, Pasadena, CA

August 31 – September 2, 2015



Dr. Dale Arney and Chris Jones

NASA Langley Research Center

Space Mission Analysis Branch

An Exploration Strategy for Venus

Contributors

Mission Architecture

Craig Hutchinson—SMAB	Paul Speth—SMAB	D.R. Komar—VAB
Matt Simon—SMAB	Taneal Fulton—LARSS	Bill Moore—NIA

Vehicle Concept

Sharon Jefferies—SMAB	Rafael Lugo—AMA/AFESB	John Van Norman—AMA/AFESB
Dave Cornelius—AMA	Mark Moore—ASAB	Carlie Zumwalt—AFESB
John Dec—STSB	Tom Ozoroski—AMA/ASAB	Alan Wilhite—NIA

Proof of Concept

Dave North—SMAB	Anthony Hennig—LARSS	James Lana—RD
Julie Williams-Byrd—SMAB	Jessica Snyder—LARSS	Yi Lin—RD
Zack Bassett—LARSS	Mia Siochi—RD	Gary Wainwright—AMC
Jim Clark—LARSS	Godfrey Sauti—RD	Rob Andrews—AMC

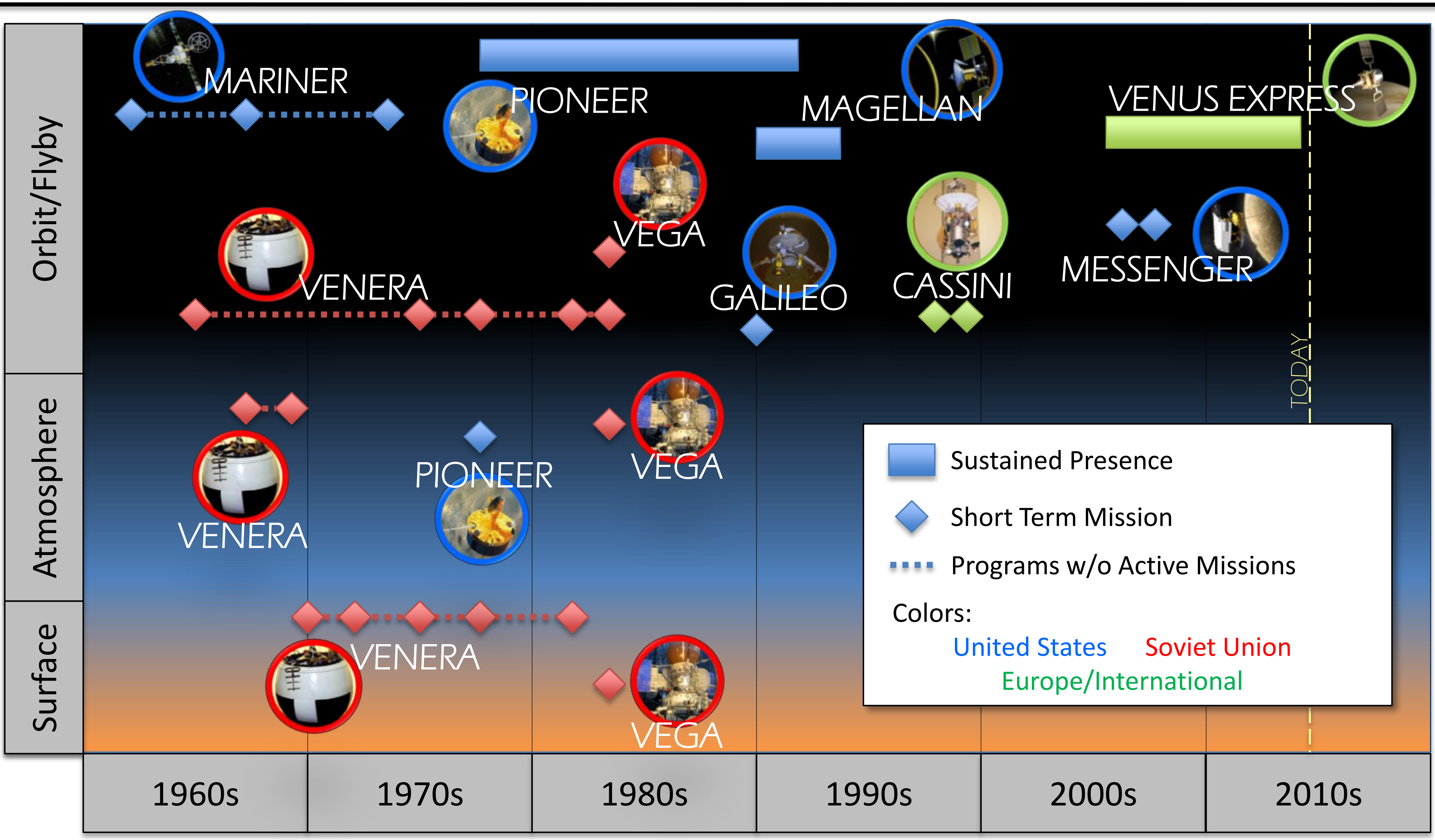
Study Support

J.D. Reeves—SMAB	Dave Helton—ACL	Josh Sams—ACL
Kevin Earle—SMAB	Bob Evangelista—ACL	Leanne Troutman—ACL
Nicole McDonald—LAMPS/SMAB	Chris Keblitis—ACL	
Kandyce Goodliff—SMAB	Kevin Greer—ACL	

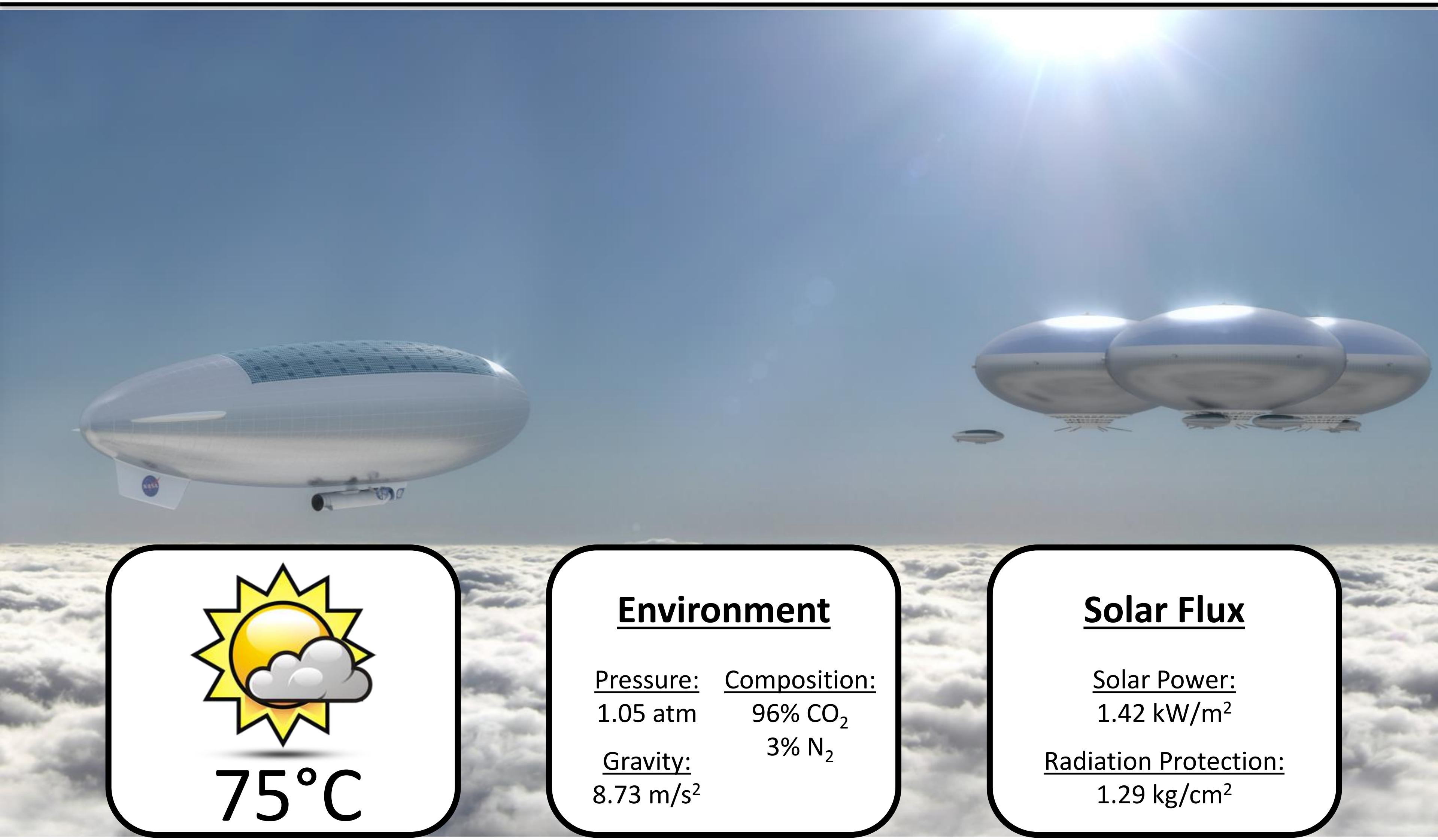
What does the future look like?

- **Humans as a spacefaring civilization: Humans explore to…**
  - Satisfy curiosity
  - Acquire resources
  - Start a new life
- **Venus is a destination for humans to reside**
  - Nearest planet to Earth
  - Abundance of useful resources: energy, carbon, oxygen, nitrogen
  - Atmosphere is a hospitable environment
- **Venus as a stepping stone to Mars**
  - Orbital mechanics:
    - Shorter missions (14 month total duration) with similar propulsion requirements
    - Abort-to-Earth available anytime after Venus arrival
  - Similar technologies are required and/or can be used: long-duration habitats, aerobraking/aerocapture, carbon dioxide processing
  - Serve as a test case for operations to/at/from another world

What does the past look like?



Venus Atmosphere at 50 km



75°C

Environment

Pressure:
1.05 atm

Gravity:
8.73 m/s^2

Composition:
96% CO_2
3% N_2

Solar Flux

Solar Power:
1.42 kW/m^2

Radiation Protection:
1.29 kg/cm^2

Comparison of Venus, Earth, and Mars

Venus

	Surface	At 50 km
Temperature	462°C	75°C
Solar Power	661 W/m^2	1418 W/m^2
Rad. Shielding	> 8280 g/cm^2	1290 g/cm^2
Pressure	9,330 kPa	106.6 kPa
Density	64.79 kg/m^3	1.594 kg/m^3
Gravity	8.87 m/s^2	8.73 m/s^2

Earth

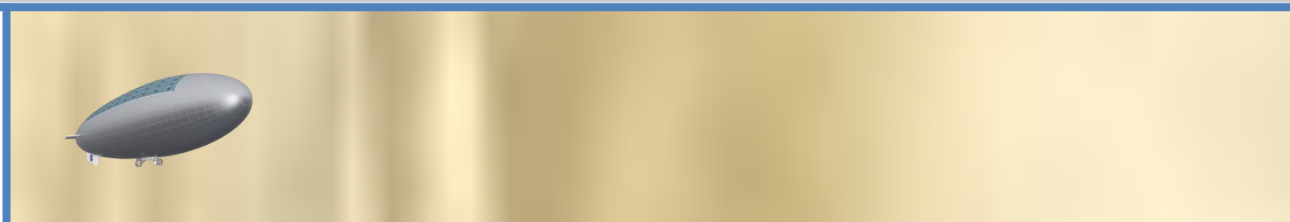
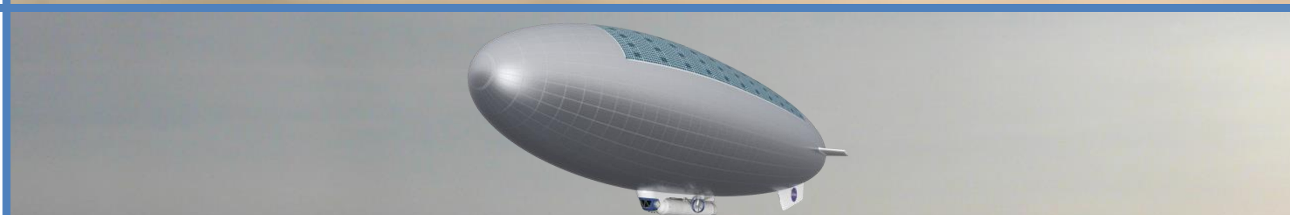
Temperature	15°C
Solar Power	1060 W/m^2
Rad. Shielding	1020 g/cm^2
Pressure	101.3 kPa
Density	1.240 kg/m^3
Gravity	9.81 m/s^2

Mars

Temperature	-63°C
Solar Power	590 W/m^2
Rad. Shielding	16 g/cm^2
Pressure	0.64 kPa
Density	0.016 kg/m^3
Gravity	3.71 m/s^2

Images: http://apod.nasa.gov/apod/ap050903.html, http://earthobservatory.nasa.gov/IOTD/view.php?id=77085, http://apod.nasa.gov/apod/ap010718.html

Venus Evolutionary Exploration Program

Phase 1: Robotic Exploration	
Phase 2: 30-day Crew to Orbit	
Phase 3: 30-day Crew to Atmosphere	
Phase 4: 1-year Crew to Atmosphere	
Phase 5: Permanent Human Presence	

Mission Operations Overview

- **Longitudinal winds of 85 to 100 m/s at Equator → ~110 hrs to circle planet**
- **Northward winds up to 5 m/s**
- **Airship "rides" longitudinal winds while using propulsion to counter poleward drift**
- **Daytime Operations:**
  - Shortest day is ~44 hrs.
  - Power systems sized for dash velocity: 15 m/s
- **Nighttime Operations:**
  - Longest night is ~66 hrs.
  - Energy storage sized for low energy vel.: 3 m/s
  - Poleward drift is countered with higher daytime velocity
- **Payload**
  - Science Instruments (Robotic and Human)
  - Atmospheric Habitat (Human only)
  - Ascent Vehicle and Habitat (Human only)

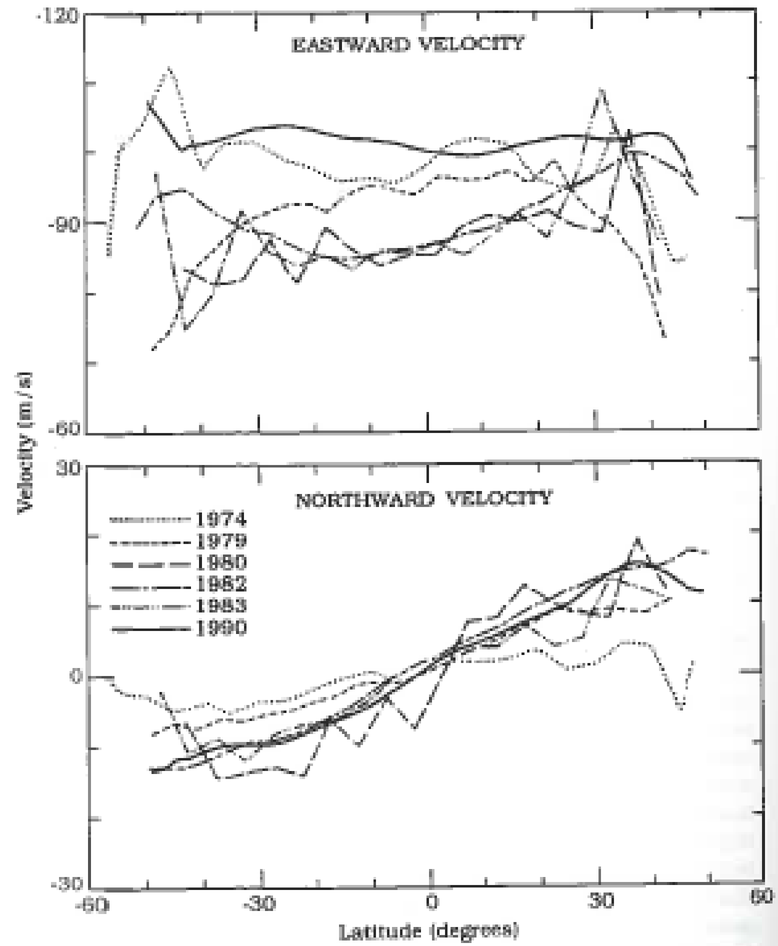
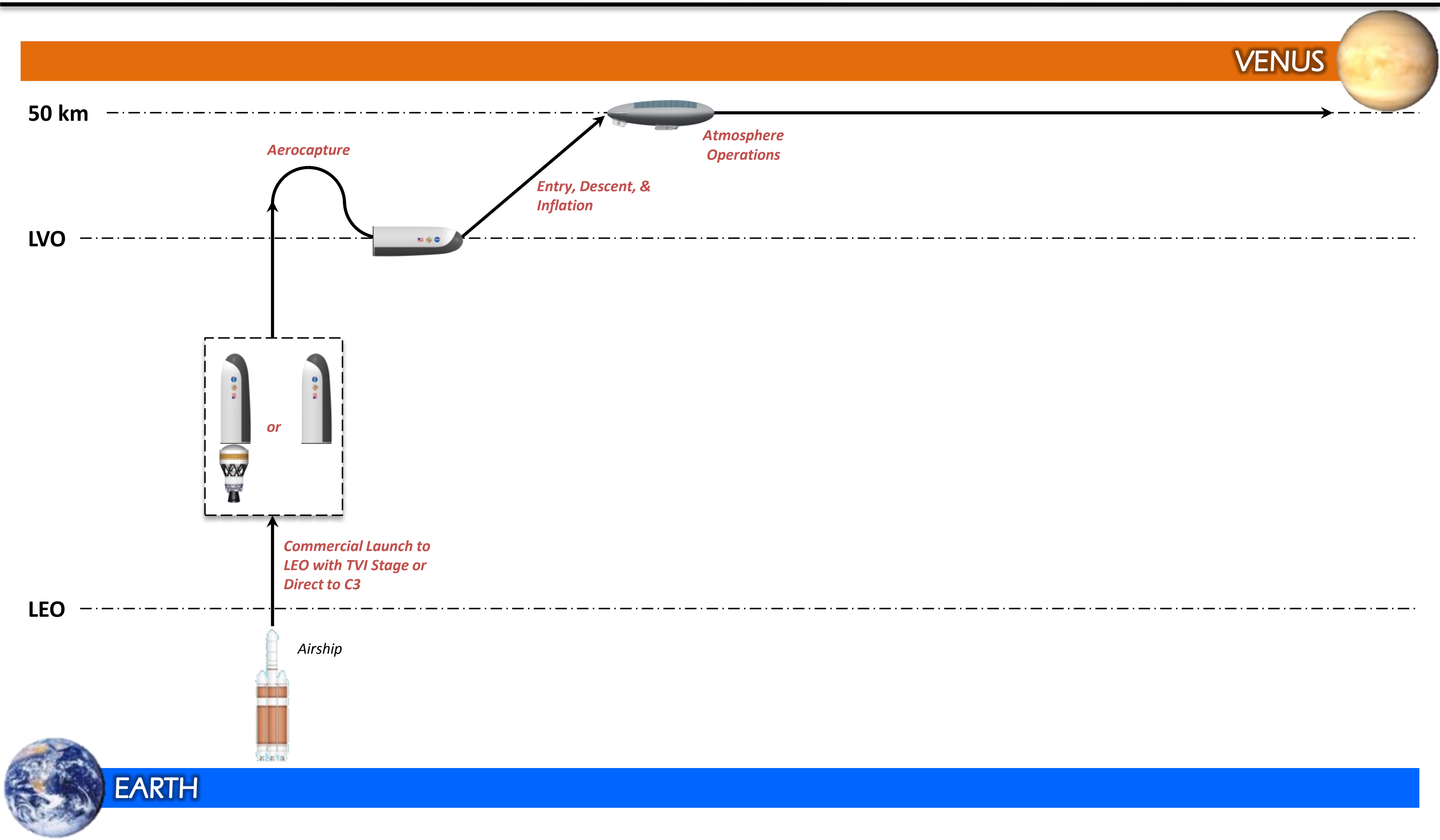


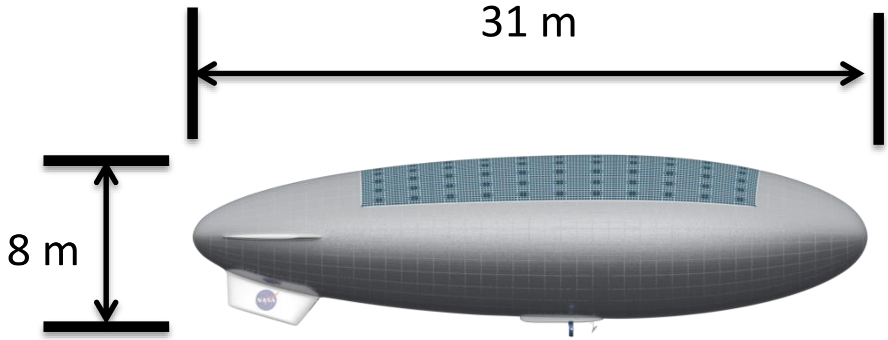
Image:Bougher, Hunten, and Phillips. *Venus II: Geology, Geophysics, Atmosphere, and Solar Wind Environment*. University of Arizona Press, Tucson, AZ, p. 466, 1997.

Phase 1: Robotic Exploration

Robotic Concept of Operations



Airship Concept – Robotic Mission



Element	Mass
Payload	750 kg
Helium|Tanks	118|96 kg
Hull	201 kg
Power and Propulsion	217 kg
Total	**1,382 kg**

Requirement	Value
Volume	1,118 m^3
Ops|Regen|Total Power	9.1|2.5|11.6 kWe
Solar Array Area	50.4 m^2
Energy Storage	92.9 kWh
Energy Storage Time	66 hrs

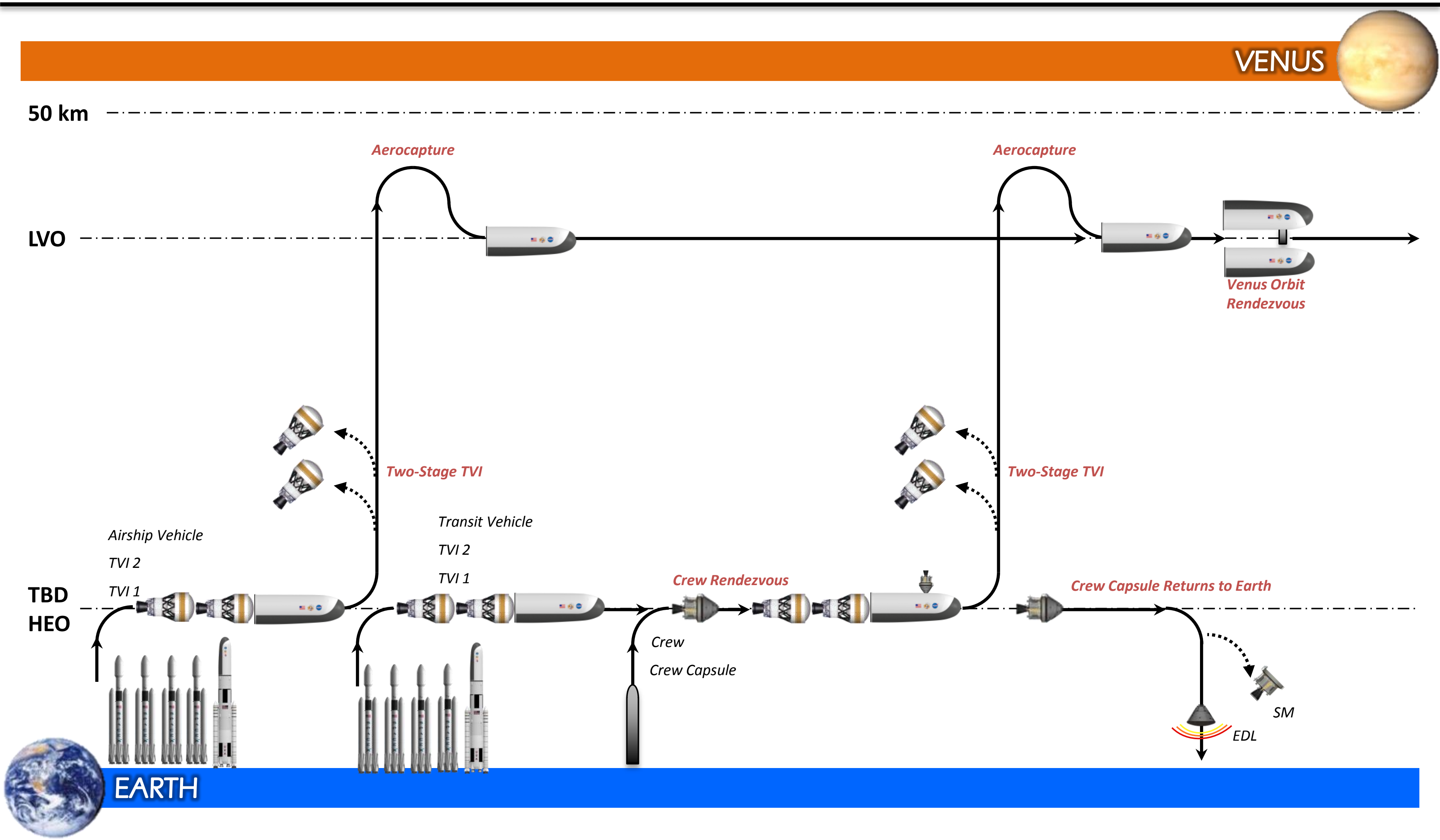
Science Platform Options

Platform		Orbiter	Airship	Drop Probes	Drop Balloons	Lander
Notional Mass Range				50-200 kg	50-200 kg	650-750 kg
I. Understand atmospheric formation, evolution, and climate history.	A. How did the atmosphere of Venus form and evolve?		●	●	●	●
	B. What is the nature of the radiative and dynamical energy balance on Venus (e.g. super-rotation and greenhouse)?	◉	●	○	◉	○
	C. What are the morphology, chemical makeup, and variability of the Venus clouds, their roles in the radiative/dynamical energy balance, and impact on climate? Does habitable zone harbor life?	○	●	◉	◉	
II. Understand the nature of interior-surface-atmosphere interactions.	A. Did Venus ever have surface or interior liquid water and what role has the greenhouse effect had on climate through Venus' history?		○	○	○	●
	B. How have the interior, surface, and atmosphere interacted as a coupled climate system over time?	○	◉	○	◉	◉
III. Determine the evolution of the surface and interior.	A. How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonics or resurfacing varied with time?	◉	○	○	○	◉
	B. How did Venus differentiate and evolve over time? Is the crust nearly all basalt or are there significant volumes of more differentiated (silica-rich) crust?	○	○			◉

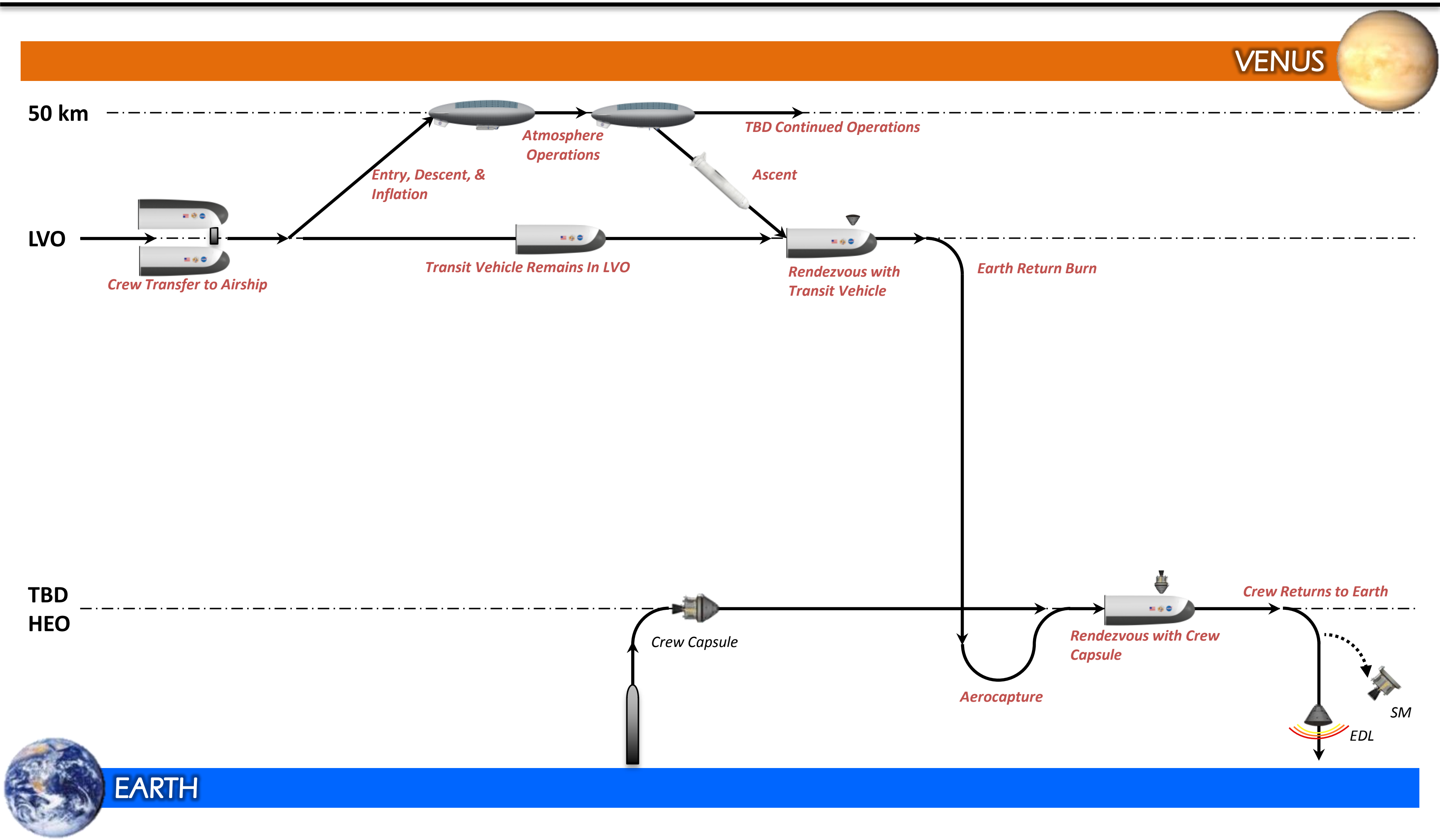
Legend: ● Major Contribution, ◉ Moderate Contribution, ○ Minor Contribution

Phase 3: 30-Day Human Exploration

Human Concept of Operations (1 of 2)

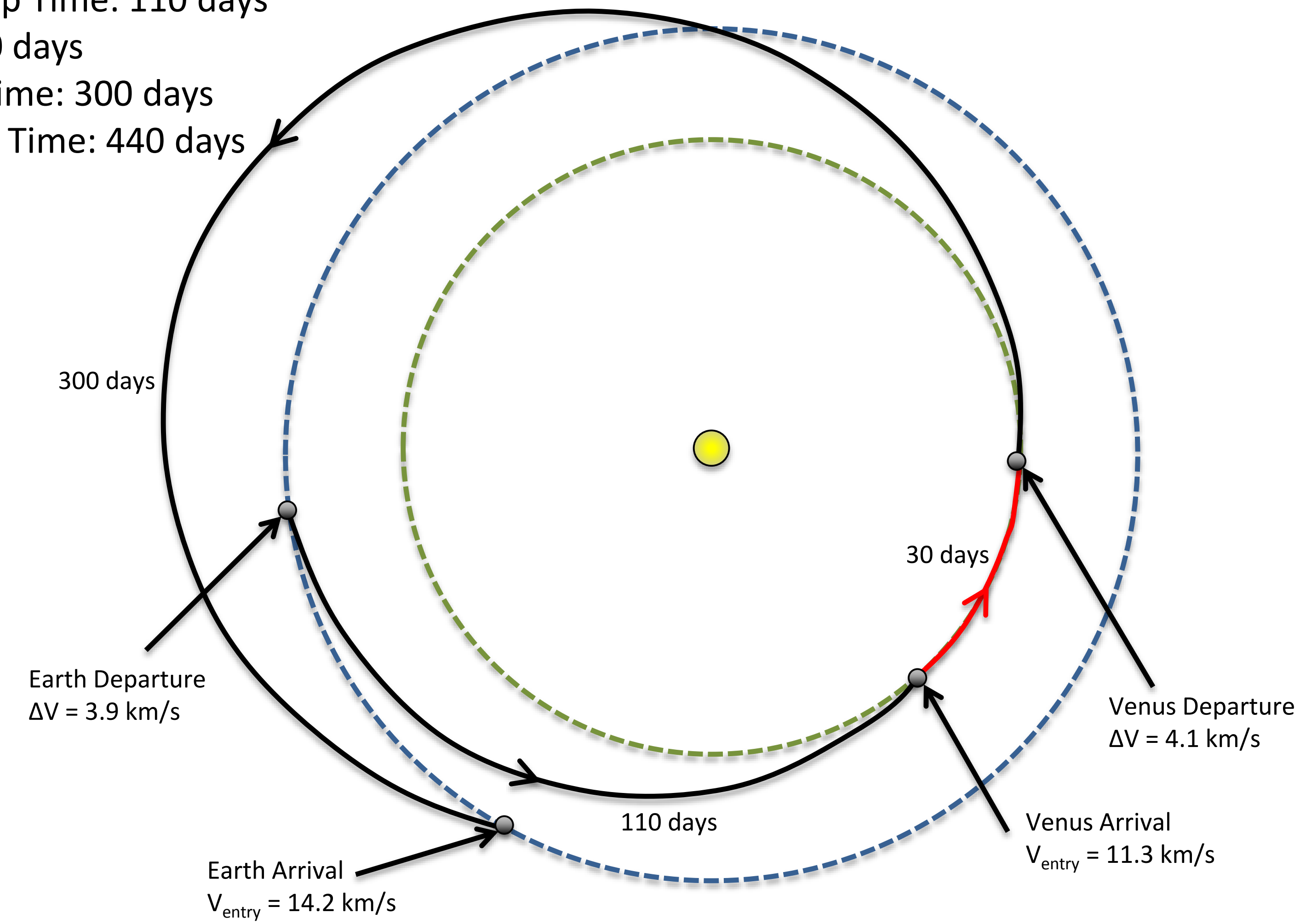


Human Concept of Operations (2 of 2)



Round-Trip Venus Mission with 30 Day Stay

Outbound Trip Time: 110 days
Stay Time: 30 days
Return Trip Time: 300 days
Total Mission Time: 440 days

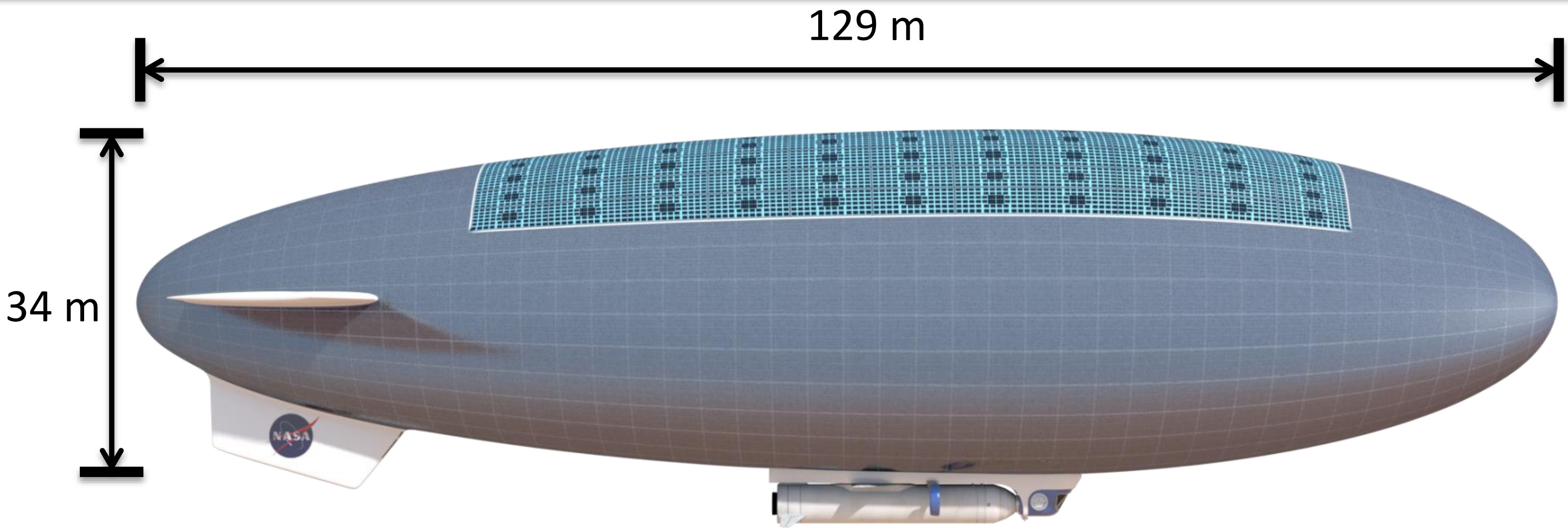


Human Mission Mass Summary

Element	Mass (t)
Atmospheric Habitat	5.1
Ascent Habitat	2.2
Ascent Vehicle	62.7
Airship	25.8
EDI and Aerocapture	33.3
Trans-Venus Injection Stage 2	109.4
Trans-Venus Injection Stage 1	109.4
IMLEO	**348.5**

Element	Mass (t)
Transit Habitat	20.2
Trans-Earth Injection Stage	52.4
Aerocapture	26.5
Trans-Venus Injection Stage 2	63.3
Trans-Venus Injection Stage 1	103.9
IMLEO	**266.3**

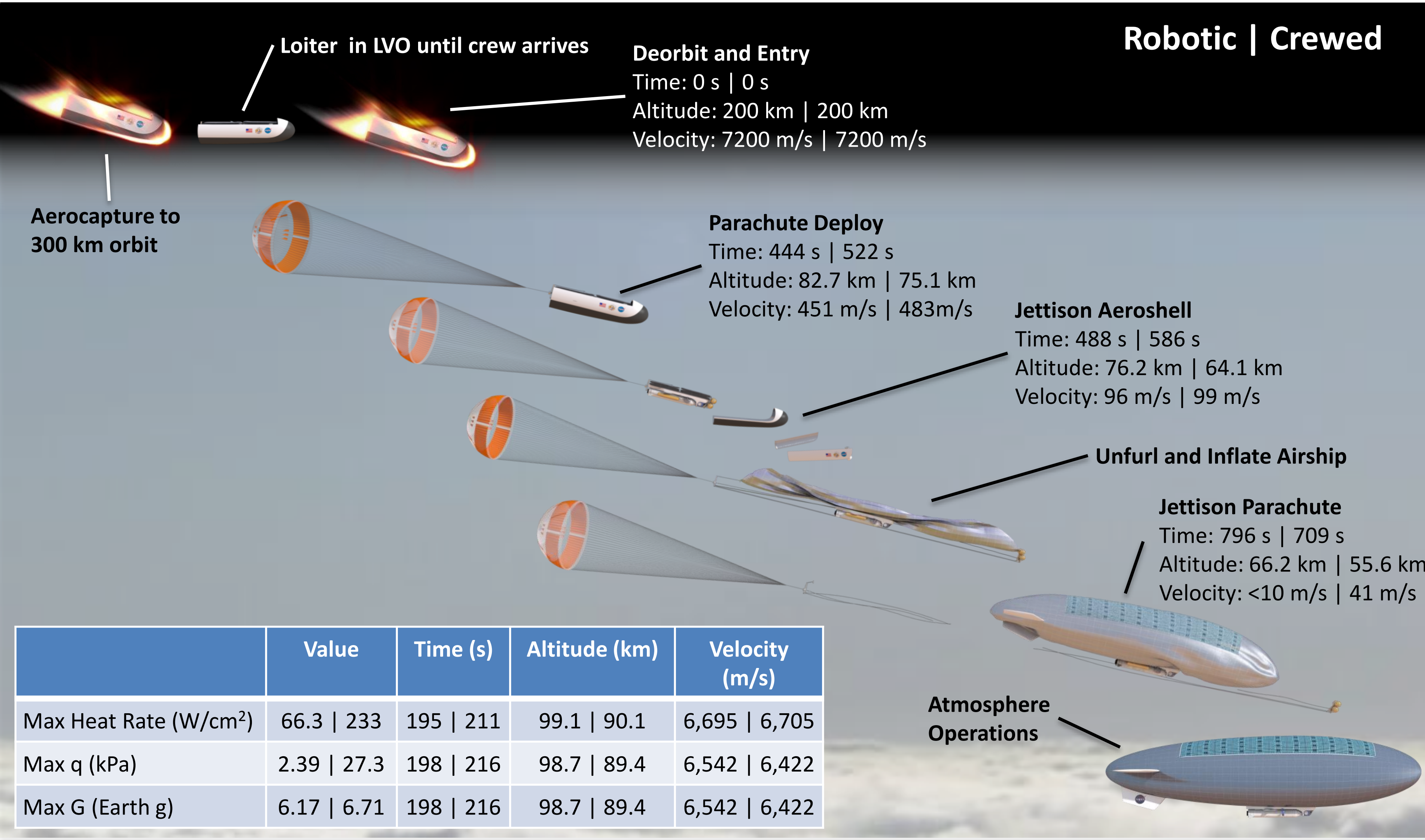
Airship Concept – Human Mission



Element	Mass
Payload	70,000 kg
Helium|Tanks	8,183|6,623 kg
Hull	6,455 kg
Power and Propulsion	4,511 kg
Total	**95,776 kg**

Requirement	Value
Volume	77,521 m^3
Ops|Regen|Total Power	187|53|240 kWe
Solar Array Area	1,044 m^2
Energy Storage	1,959 kWh
Energy Storage Time	66 hrs

Aerocapture, Entry, Descent, and Inflation Profile

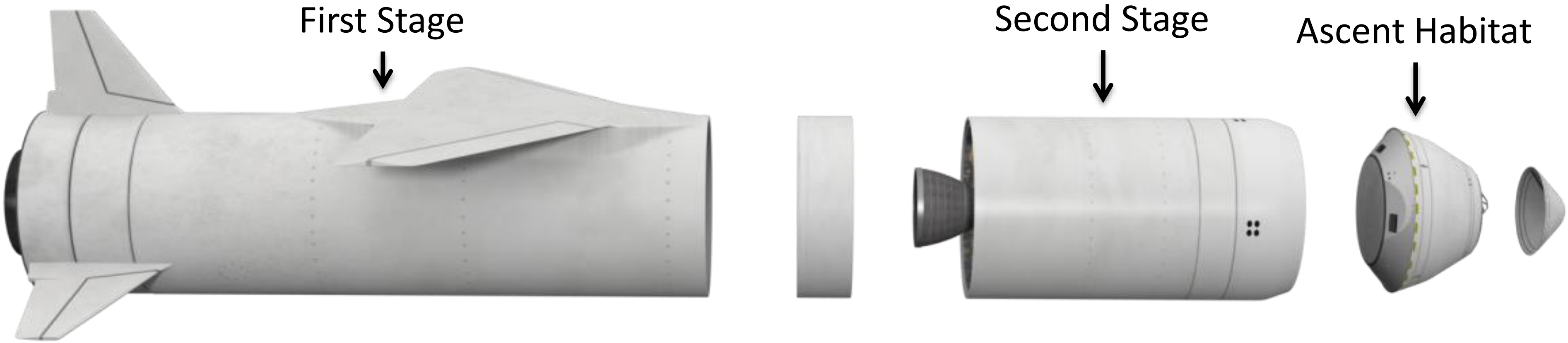


	Value	Time (s)	Altitude (km)	Velocity (m/s)
Max Heat Rate (W/cm^2)	66.3 | 233	195 | 211	99.1 | 90.1	6,695 | 6,705
Max q (kPa)	2.39 | 27.3	198 | 216	98.7 | 89.4	6,542 | 6,422
Max G (Earth g)	6.17 | 6.71	198 | 216	98.7 | 89.4	6,542 | 6,422

Habitat Overview

Transit Habitat	Atmospheric Habitat	Ascent Habitat
2 crew, 400 days	2 crew, 30 days	2 crew, up to 1 day
Contingency EVA only	No EVA	No EVA
Similar to DSH: 20.2 t	Similar to SEV: 5.1 t	Similar to small capsule: 2.2 t
44 m^3 at 1 atm	21 m^3 at 1 atm	4.6 m^3 at 1 atm
Power: 12 kWe	Power: 3 kWe	Power: 1 kWe

Venus Ascent Vehicle



Mission Parameters

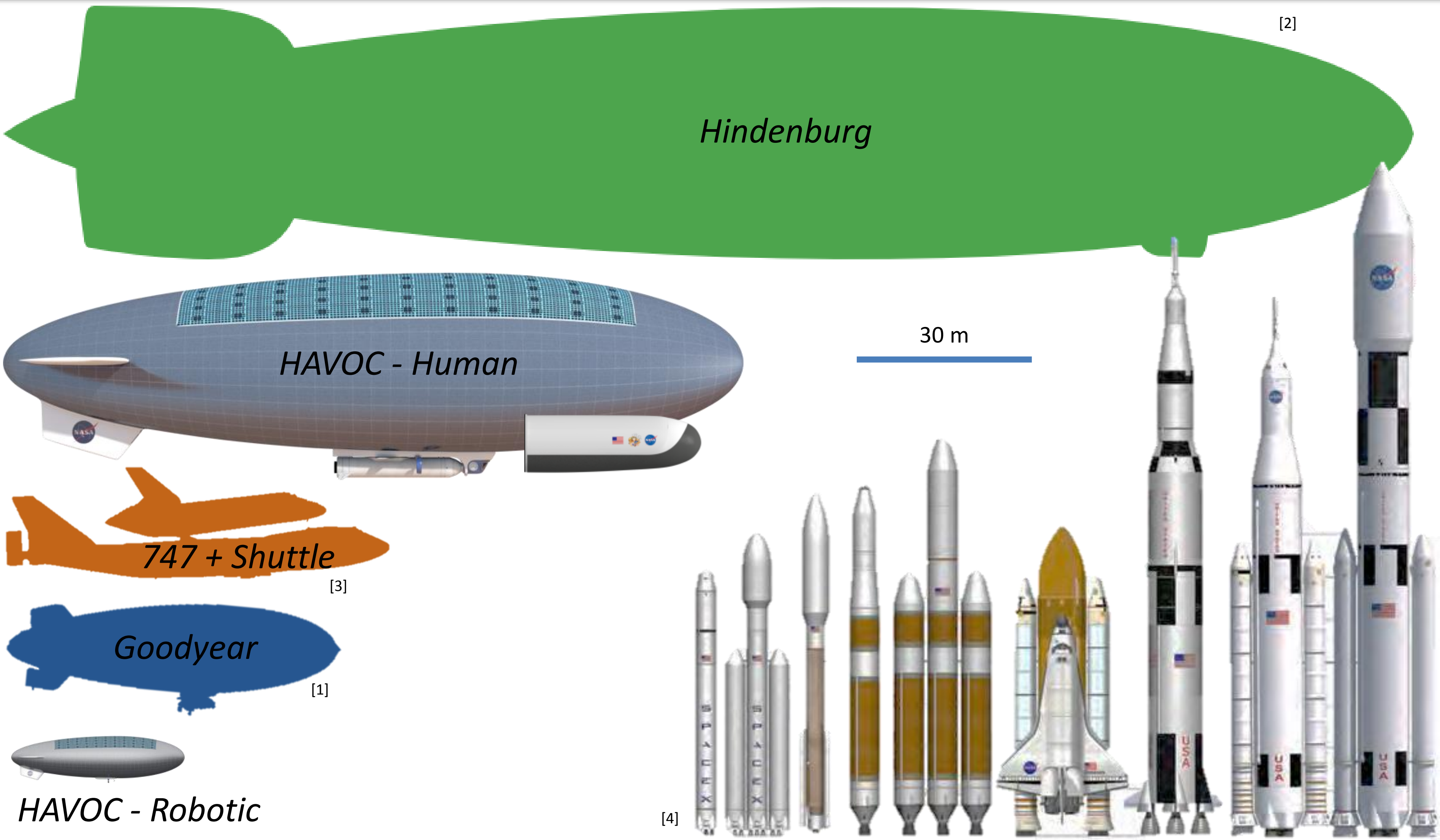
- Ascend from 50 km to orbit to rendezvous with TEI stage and transit habitat
- Estimated 9,000 m/s total ΔV

Configuration

- 2 Crew, Minimal Duration Ascent Habitat
- Two stage ascent
- LOX/RP-1 propellant (easier thermal management than cryogenic fuels)
- Estimated 63 t Gross Mass

Conclusion

Venus Airship Size Comparison

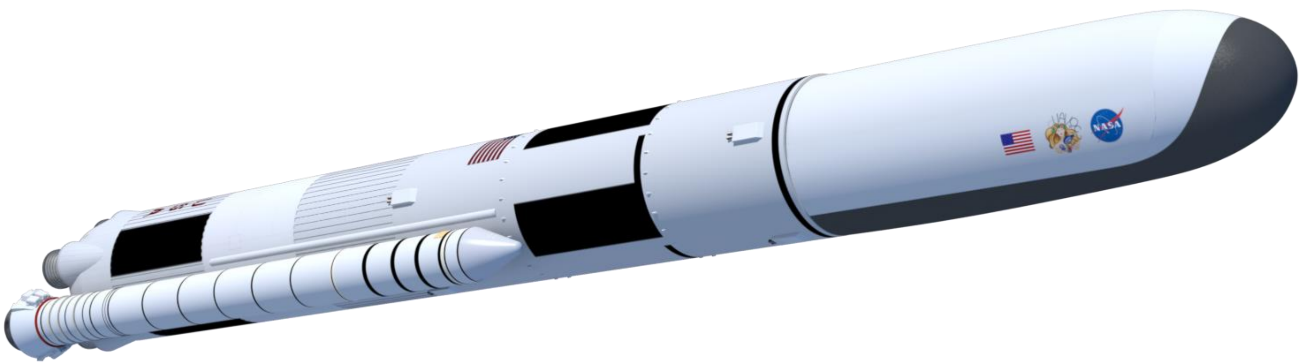


HAVOC YouTube Video

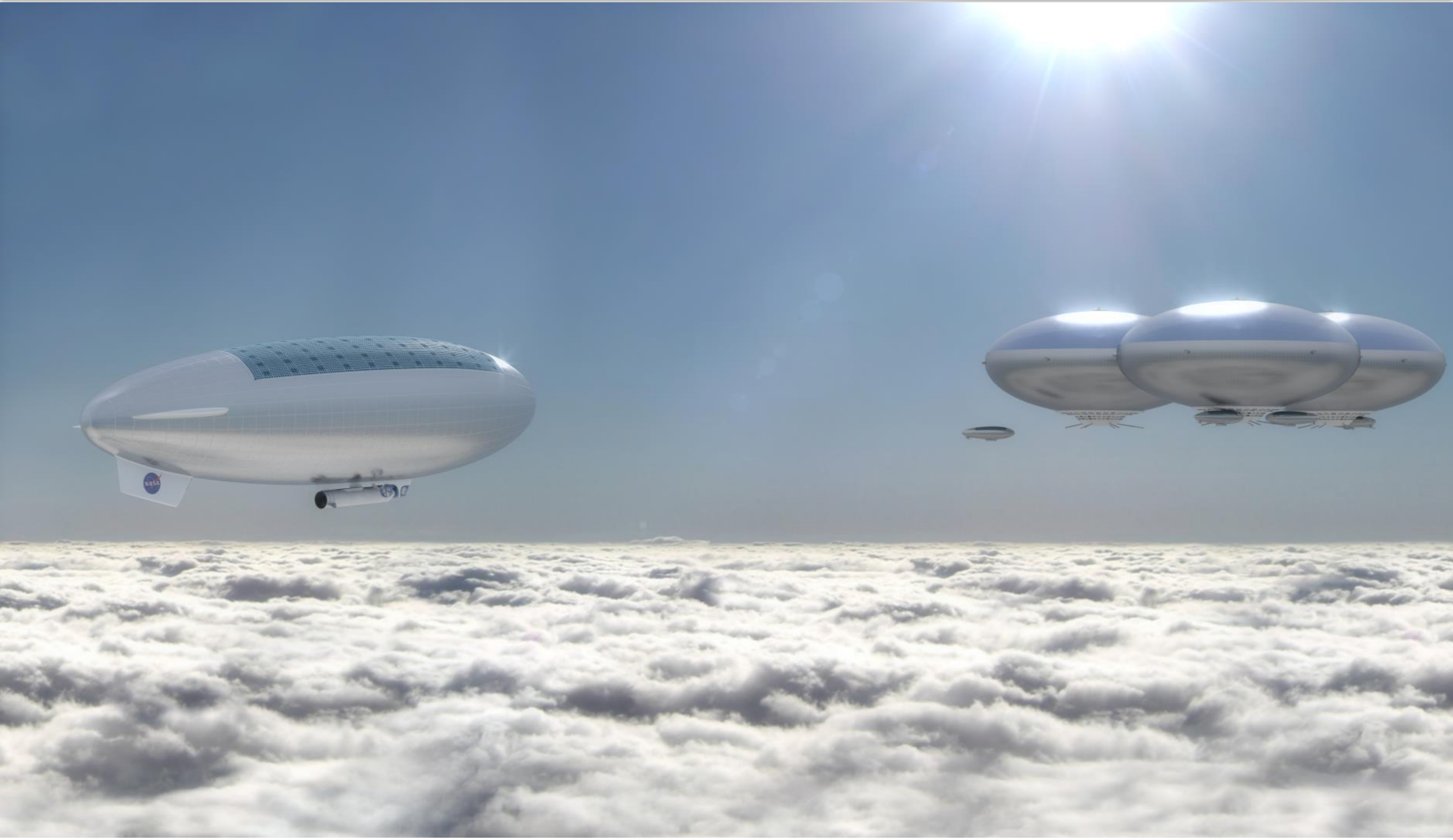
- URL: https://youtu.be/0az7DEwG68A

Summary

- **HAVOC developed an evolutionary exploration plan that presents Venus as another destination for human exploration in space**
- **Initial analysis shows that robotic and human exploration of Venus with airships is feasible**
  - Capability Development Needs: human-scale aeroentry vehicles, advanced supersonic decelerators, long-duration cryogenic storage, Venus and Earth aerocapture, rapid airship inflation during descent
  - Many technologies and capabilities are complementary to Mars missions
- **Deeper dives into sizing, trajectories, and operations would refine architectural and vehicle understanding**
- **Venus, with its relatively hospitable upper atmosphere, can play a role in humanity's future in space.**



Questions?



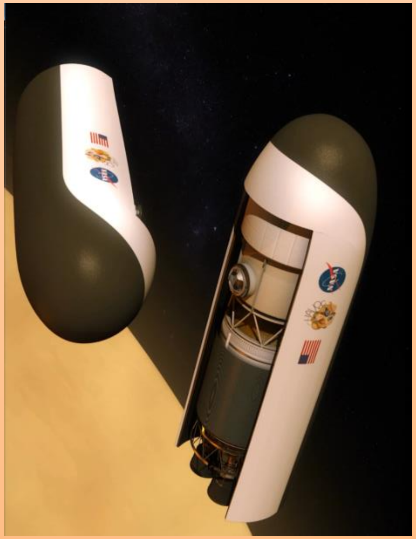
Backup Slides

References

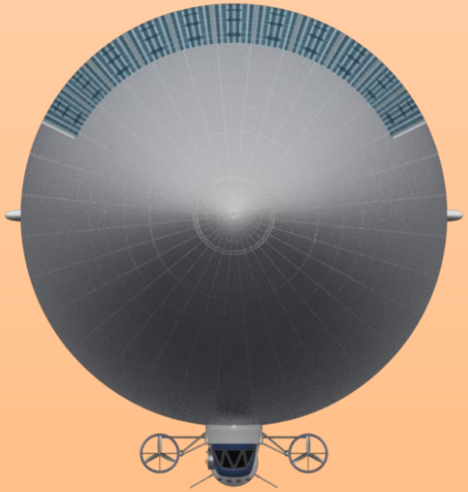
1. Goodyear blimp picture: Stuart Grout, http://www.flickr.com/photos/pigpilot/7132847251/
2. Hindenburg outline: http://en.wikipedia.org/wiki/File:Building_and_ship_comparison_to_the_Pentagon2.svg
3. Shuttle Carrier Aircraft picture from Dryden 747 SCA Graphics Collection: http://www.dfrc.nasa.gov/Gallery/Graphics/B-747-SCA/index.html
4. Launch vehicle comparison from "NASA's Space Launch System: A New National Capability"

HAVOC Products

Mission Architecture



Vehicle Concept



Proof of Concept

Deliverables

Robotic and crewed Venus Reference Architectures

Platform to support robotic and crewed missions

Demonstrations of sulfuric acid resistance and vehicle packaging/deployment

Objectives for Venus

- **Science Objectives (VEXAG—Venus Exploration Analysis Group)**
  - I. Understand atmospheric formation, evolution, and climate history on Venus.
  - II. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.
  - III. Determine the evolution of the surface and interior of Venus.

- **Human Objectives**
  - IV. Reduce risks and advance technologies for human exploration of the solar system.
    - A. Demonstrate the ability for humans to survive and operate in deep space and around planetary bodies.
    - B. Develop advanced technologies that will enable humans to visit planetary destinations.

VEXAG Investigations and Platforms (1 of 2)

3: Directly answers	2: Major contribution
1: Minor contribution	0: Does not address

I. Understand atmospheric formation, evolution, and climate history on Venus.

II. Understand interior, surface, and atmosphere interactions over time.

Goals	Objective	Investigation	Orbital	High-Level Aerial (> 60 km)	Mid-Level Aerial (45-60 km)	Low-Level Aerial (15-45 km)	Near-Surface Aerial (0-15 km)	Single Entry Probe (no surface)	Multiple Entry Probe (no surface)	Short-Lived Lander (Single)	Short-Lived Lander (Multiple)	Long-Lived Lander (Single)	Long-Lived Lander (Multiple)	Surface System with mobility
I. Understand atmospheric formation, evolution, and climate history on Venus.	[illegible]	[illegible]	0	3	3	3	3	3	3	3	3	3	3	3
		[illegible] escape rates	0	3	3	3	3	3	3	3	3	3	3	3
	B. What is the nature of the radiative and dynamical energy balance on Venus (e.g. super-rotation and greenhouse)?	1. Characterize atmospheric super-rotation and global circulation: zonal/meridional winds (surface to 120 km)	2	3	3	3	2	1	1	2	2	3	3	2
		2. Determine atmospheric radiative balance and temperature profile (surface to 140 km)	2	2	3	3	1	2	3	0	0	0	0	0
		3. Characterize small-scale atmospheric vertical motion (due to convection and local/gravity waves)	1	3	3	3	1	1	1	0	0	0	0	0
	C. What are the morphology, chemical makeup, and variability of the Venus clouds, their roles in the radiative/dynamical energy balance, and impact on climate? Does habitable zone harbor life?	1. Characterize meteorology/chemistry of middle cloud layer: aerosols, particles, vertical motion	1	1	3	1	0	2	3	0	0	0	0	0
		2. Characterize greenhouse aerosols and gases: composition, production & loss, role in radiative balance	1	1	3	1	0	2	3	0	0	0	0	0
		3. Characterize lightning/discharge strength, frequency, variation; determine role in trace gas/aerosols	2	2	2	2	0	0	0	0	0	0	0	1
		4. Characterize biologically-relevant cloud/gas chemistry, including 13C/12C and complex organics	1	3	3	3	3	3	3	3	3	3	3	3
II. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.	[illegible] liquid water and what role has the greenhouse effect had on climate through Venus' history?	[illegible]	1	3	3	3	3	3	3	3	3	3	3	3
		2. Characterize areas that exhibit different formation epochs; determine role of water in tesserae	0	0	0	0	1	0	0	1	3	1	3	2
		3. Search for hydrous minerals and greenhouse gases trapped in surface rocks	0	0	0	0	0	0	0	2	3	2	3	3
	B. How have the interior, surface, and atmosphere interacted as a coupled climate system over time?	1. Measure noble gases, elemental composition and isotopic ratios in atmosphere and solid samples	0	3	3	3	3	3	3	3	3	3	3	3
		2. Evaluate characteristics of weathering rinds and composition of rock beneath	0	0	0	0	0	0	0	2	3	3	3	3
		3. Determine abundance/altitude profile of reactive species, greenhouse gases, condensables	2	2	2	2	2	1	2	0	1	0	1	1
		4. Determine sulfur cycle from surface isotopic ratios and atmospheric measurements of sulfur compounds	2	2	2	2	2	1	2	0	1	0	1	1

VEXAG Investigations and Platforms (2 of 2)

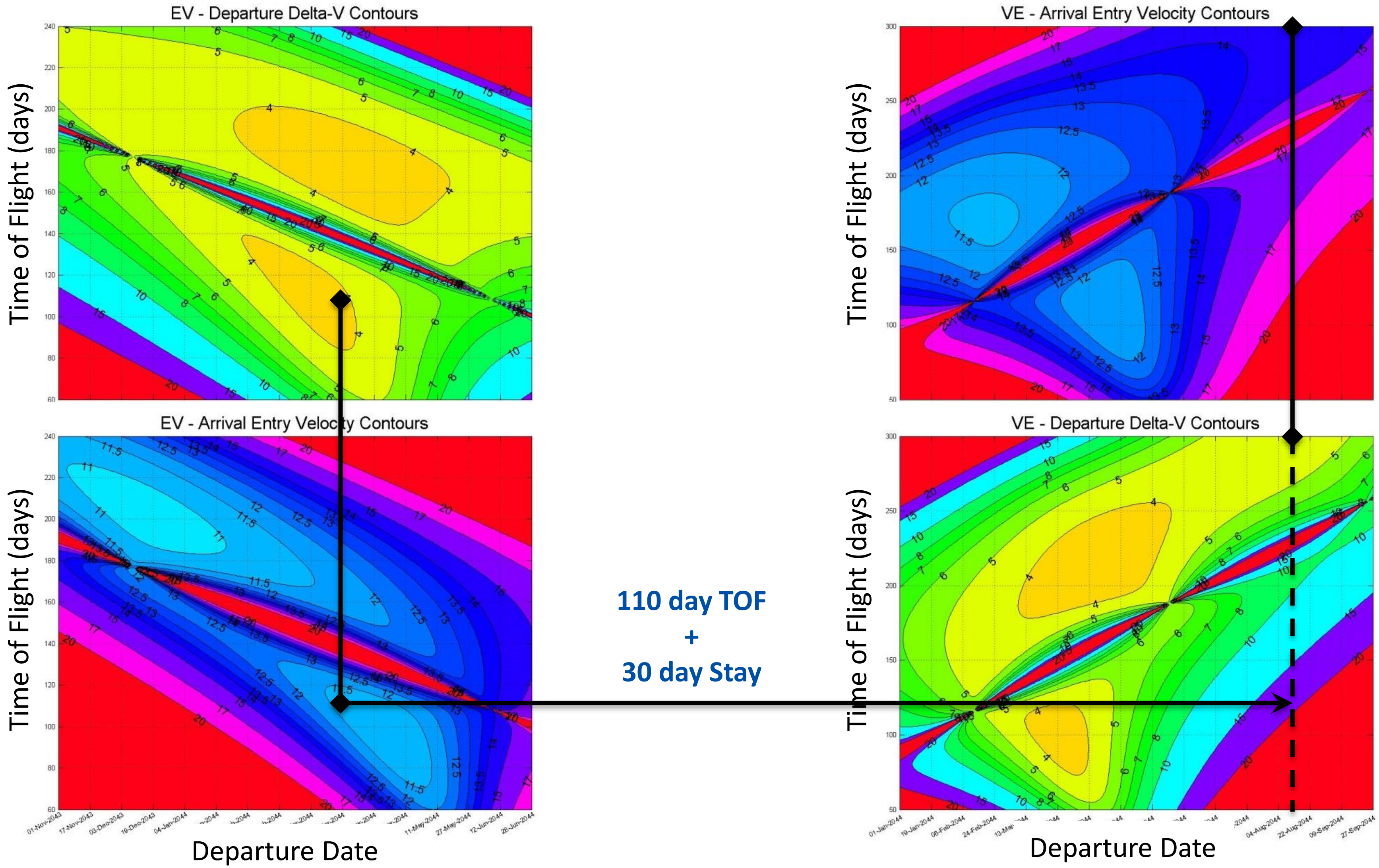
3: Directly answers	2: Major contribution
1: Minor contribution	0: Does not address

Goals	Objective	Investigation	Orbital	High-Level Aerial (> 60 km)	Mid-Level Aerial (45-60 km)	Low-Level Aerial (15-45 km)	Near-Surface Aerial (0-15 km)	Single Entry Probe (no surface)	Multiple Entry Probe (no surface)	Short-Lived Lander (Single)	Short-Lived Lander (Multiple)	Long-Lived Lander (Single)	Long-Lived Lander (Multiple)	Surface System with mobility
III. Determine the evolution of the surface and interior of Venus	A. How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time?	...face	2	0	0	0	3	2	3	1	1	1	1	2
		...ratios	0	0	0	0	0	0	0	2	3	3	3	3
		3. Characterize structure, dynamics, history of interior and effects on surface geology	3	3	3	3	3	1	1	2	2	3	3	2
		4. Determine contemporary rates of volcanic and geologic activity	3	1	1	1	2	1	2	0	0	3	3	0
		5. Determine absolute rock ages at locations that constrain global resurfacing rates	0	0	0	0	1	0	0	1	2	2	3	2
	B. How did Venus differentiate and evolve over time? Is the crust ... there significant volumes ... differentiated (silica-ri...	1. Determine composition, mineralogy, petrography of samples at key geologic sites (e.g. tesserae)	0	0	0	0	0	0	0	2	3	3	3	3
		2. Determine rock composition at regional scales through remote sensing	0	0	0	0	0	0	0	1	3	1	3	2
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	1
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	2
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	3
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	1

III. Determine the evolution of the surface and interior of Venus

Orbital	High-Level Aerial (> 60 km)	Mid-Level Aerial (45-60 km)	Low-Level Aerial (15-45 km)	Near-Surface Aerial (0-15 km)	Single Entry Probe (no surface)	Multiple Entry Probe (no surface)	Short-Lived Lander (Single)	Short-Lived Lander (Multiple)	Long-Lived Lander (Single)	Long-Lived Lander (Multiple)	Surface System with mobility
35%	55%	62%	56%	51%	46%	54%	60%	78%	72%	84%	74%

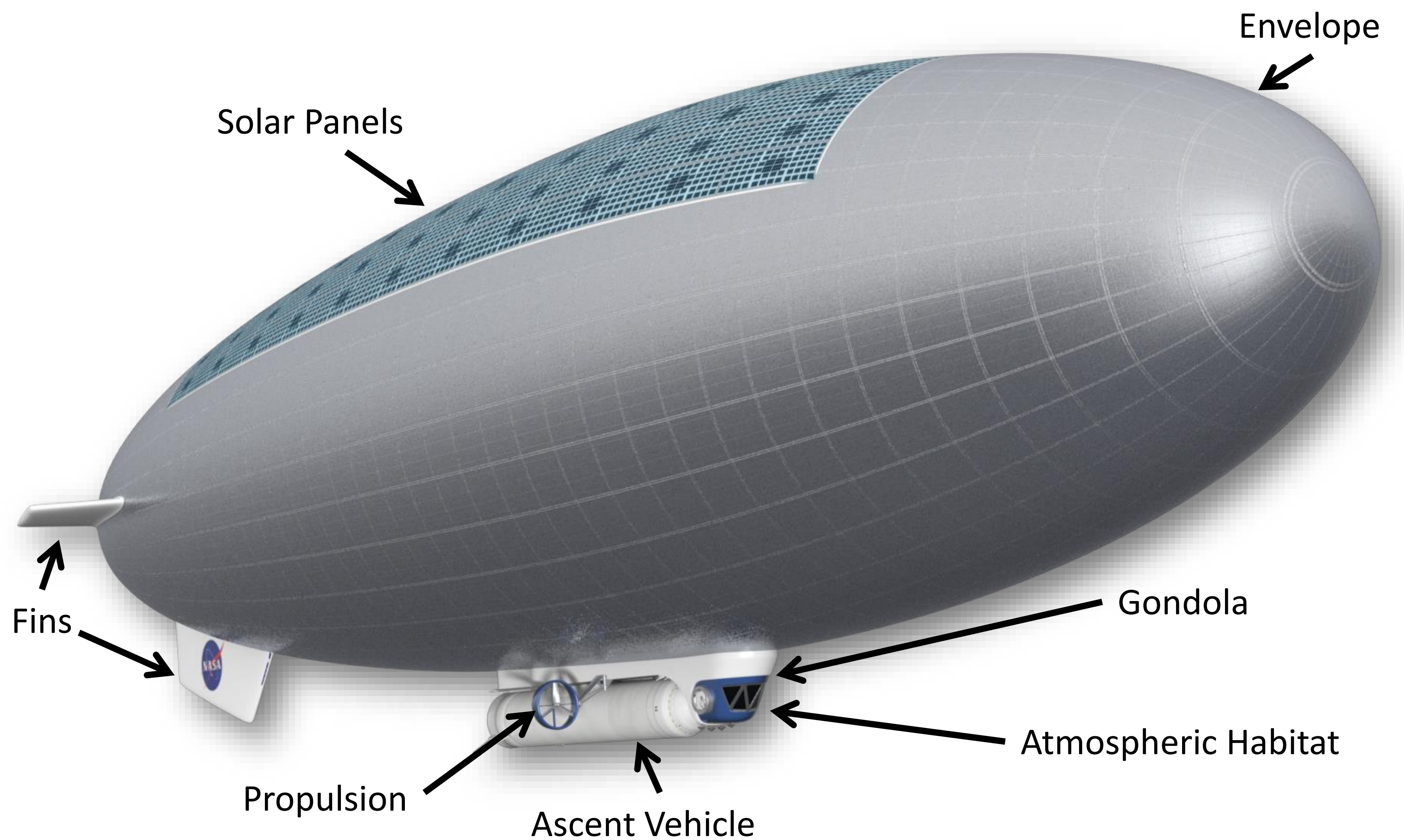
Interplanetary Trajectory for 30 Day Mission



Pre-Position Options (Human Missions)

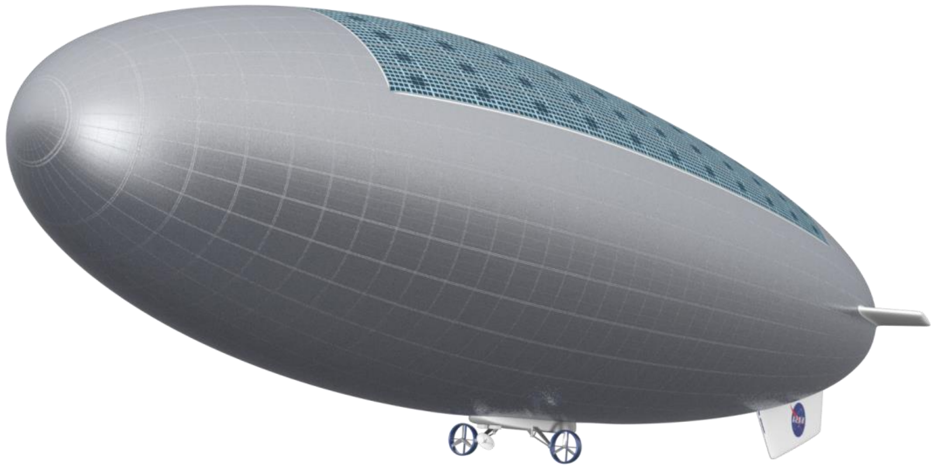
	Direct (or Earth Orbit Rendezvous, EOR)	Venus Orbit Rendezvous (VOR)	Venus Atmosphere Rendezvous (VAR)
Mass	• Earth departure stack is large • Aerocapture stack is likely prohibitive in near term	• Aerocapture stack is large but feasible	• Could use ISRU for ascent propellant (reduce delivered mass)
Operational Complexity	• Rendezvous in Earth orbit similar to other in-space assembly operations	• Rendezvous in Venus orbit poses time delay issues	• Atmospheric rendezvous is challenging for early missions
Abort Options	• Quicker abort during rendezvous/ integration operations	• Abort to Earth from Venus (~300 days) during rendezvous operations	• No abort options during rendezvous (cannot ascend to TEI stage)

Airship Concept

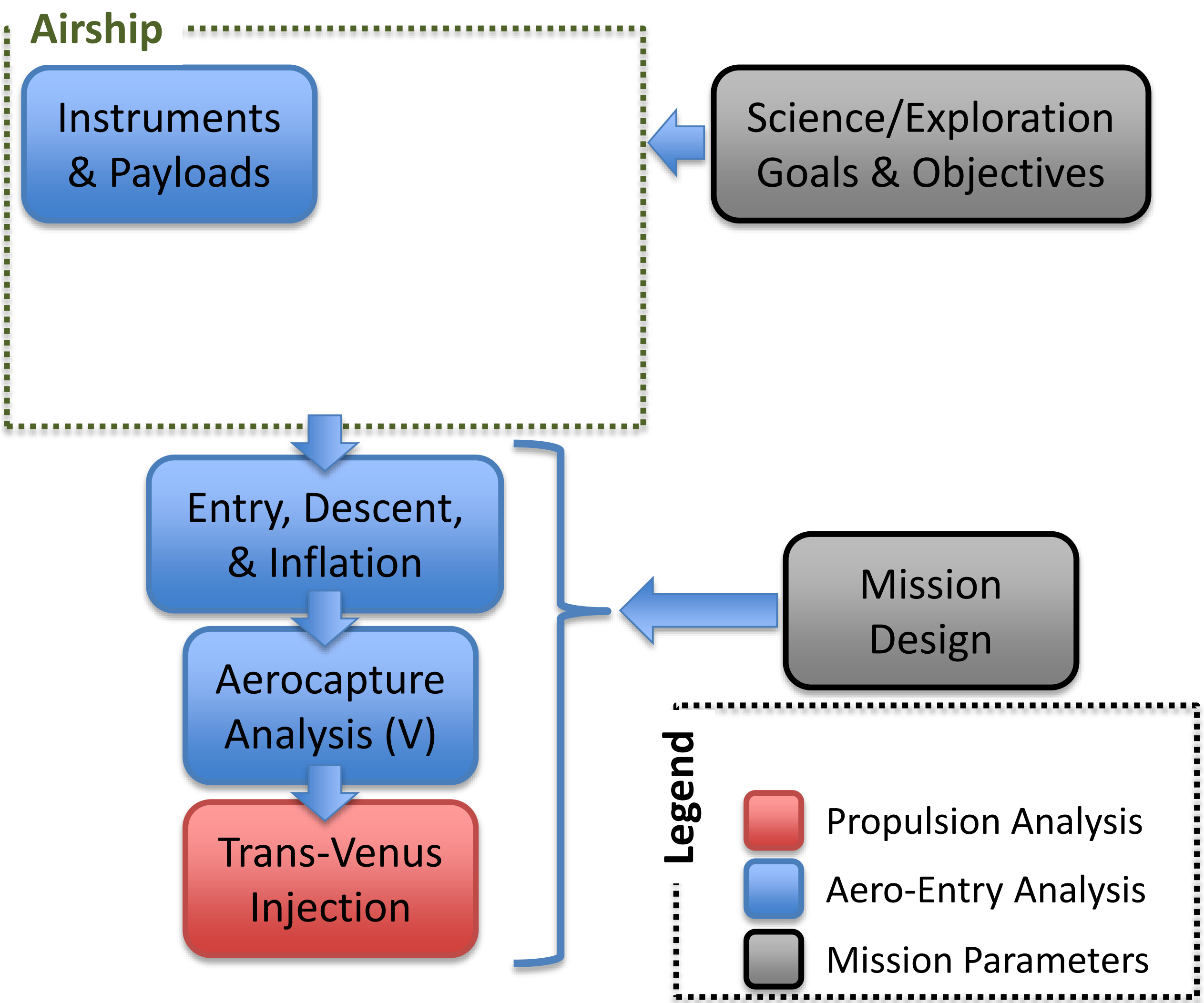


Robotic Mission Mass Summary

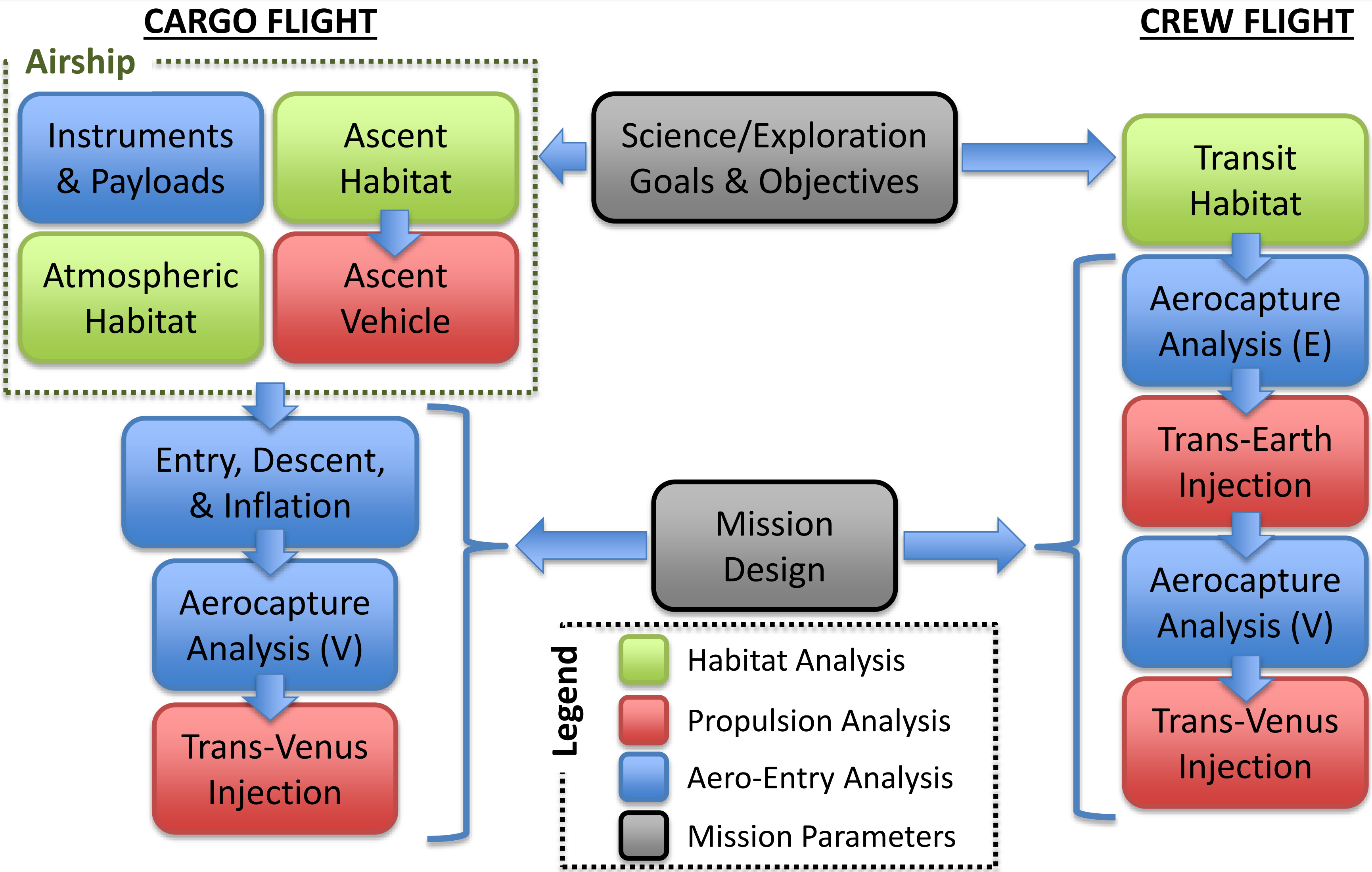
Element	Mass (kg)
Payload and Instruments	750
Airship	652
EDI and Aerocapture	1,049
Cruise Stage	122
Trans-Venus Injection Stage	4,604
IMLEO	**7,157**



Robotic Mission Analysis



Human Mission Analysis (Venus Orbit Rendezvous)



Venus Flagship Mission Study (2009) Balloon Instrument Capabilities—Robotic Mission

Table 4.10: Balloon GCMS Measurement Requirements.

Resolution	0.1 AMU
Number of spectra per mission	He = 15, other noble gases = 75, CO = 75, sulfur compounds = 200 including two 3 hour campaigns with a spectrum acquired every 20 minutes
Range of measurement	1 - 150 AMU
Sensitivity	0.1 ppb Xe, Kr

Table 4.12: Balloon Net Flux Radiometer Measurement Requirements.

Resolution	11 look angles from nadir to zenith
Frequency of measurement	Every 30 minutes
Range of measurement	Two channels, 0.2 to 3 µm and 0.8 to 25 µm
Sensitivity	SN >200 from 0.2 to 3 µm, SN >100 for 8 to 25 µm
Accuracy	<5% from 0.2 to 3 µm, <10% for 8 to 25 µm

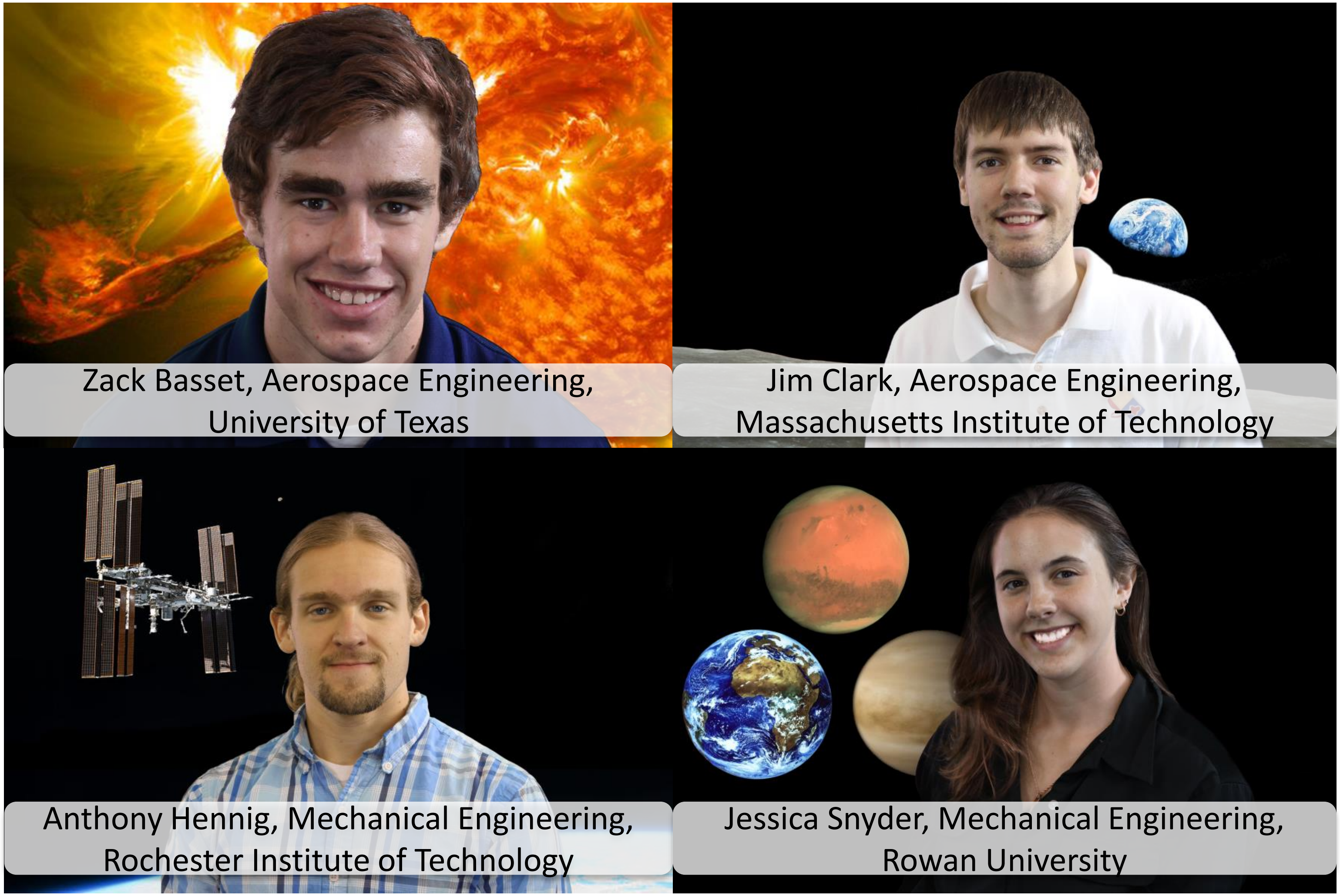
Table 4.9: Balloon Instruments.

Instrument	Mass (kg)	Power (W)	Source or Proxy
Gas Chromatograph Mass Spectrometer	11	40	Huygens, VCAM
Thermocouple, Anemometer, Pressure Transducer, Accelerometer	2	3.2	MVACS, ATMIS
Radio Tracking	0	0	–
Net Flux Radiometer	2.3	4.6	Galileo Probe
Magnetometer	1	2	JPL internal studies
Nephelometer	0.5	1.2	Pioneer Venus
Lighting Detector	0.5	0.5	FAST
TOTAL	17.3	51.5	

Range of measurement	1 – 100 m/sec
Accuracy	±10 cm/s between v = 1 – 10 m/sec; ±100 cm/s between v = 10 – 100 m/sec Wind direction ±20°
Constraints	Operates in H_2SO_4/H_2O aerosol environment

Instrument Data Source: Hall, Jeffery et al. *Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team*. Task Order NMO710851, 17 April 2009.

Summer LARSS Students



Zack Basset, Aerospace Engineering, University of Texas

Jim Clark, Aerospace Engineering, Massachusetts Institute of Technology

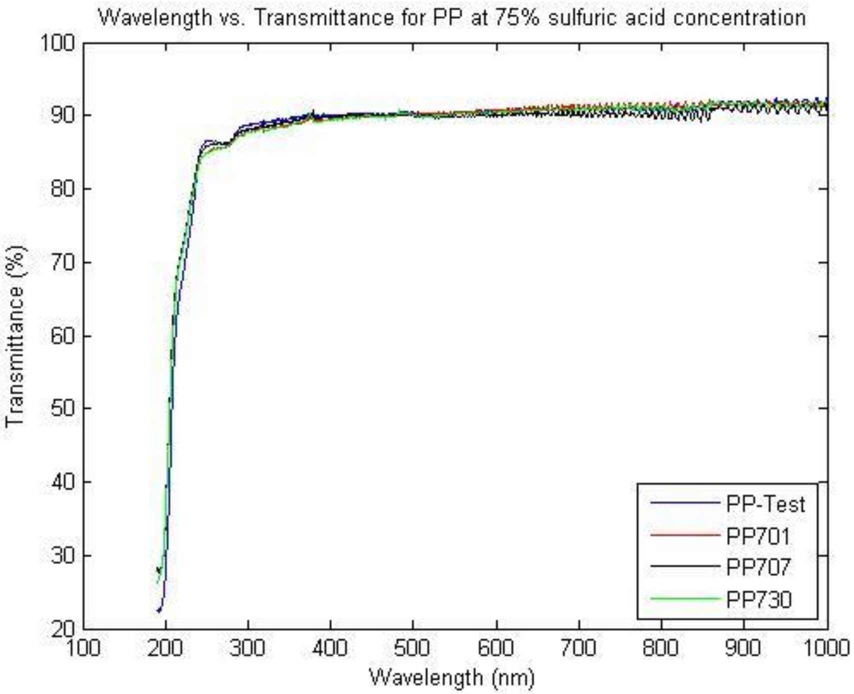
Anthony Hennig, Mechanical Engineering, Rochester Institute of Technology

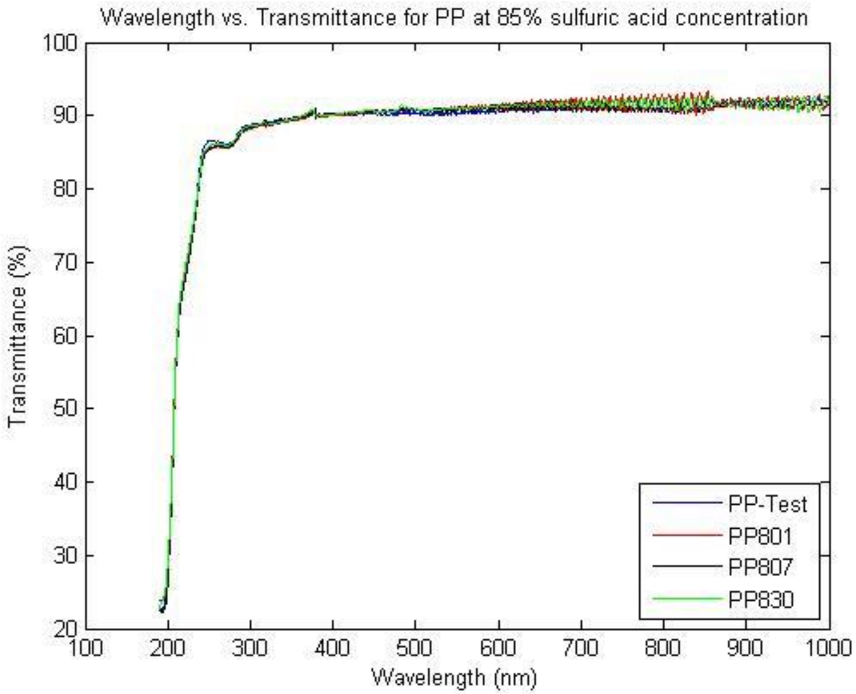
Jessica Snyder, Mechanical Engineering, Rowan University

Sulfuric Acid Test

- **Goal:** Identify material(s) suitable for protecting solar panels from concentrated sulfuric acid.
- **Method:** Soak candidate materials (FEP Teflon, PVC, PP) in acid for 1, 7, 30 days, compare physical and spectral properties against controls.
- **Analysis:** Collect data on light transmittance vs wavelength in ultra-violet, visible, and infrared spectrum.

Polypropylene Results

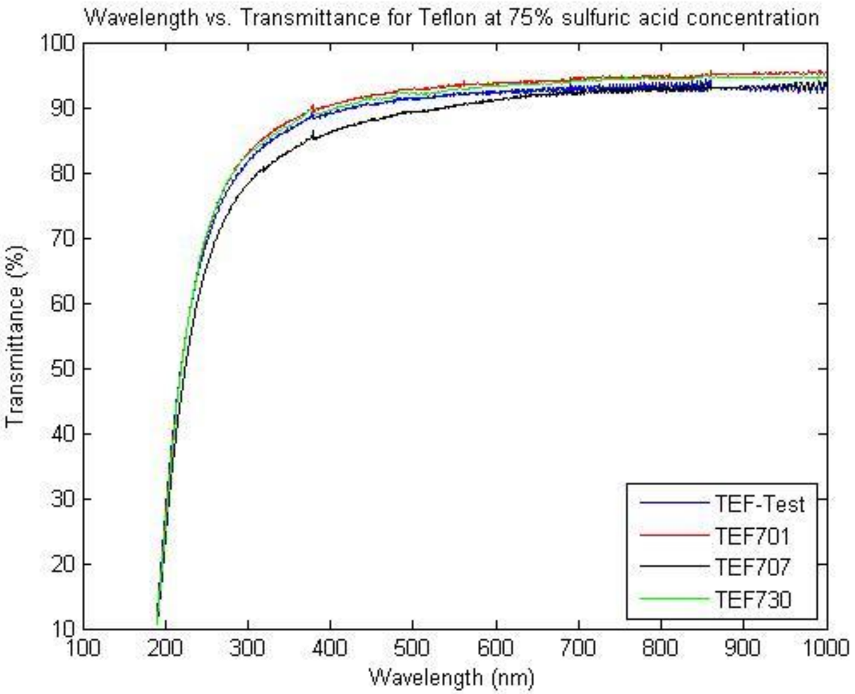


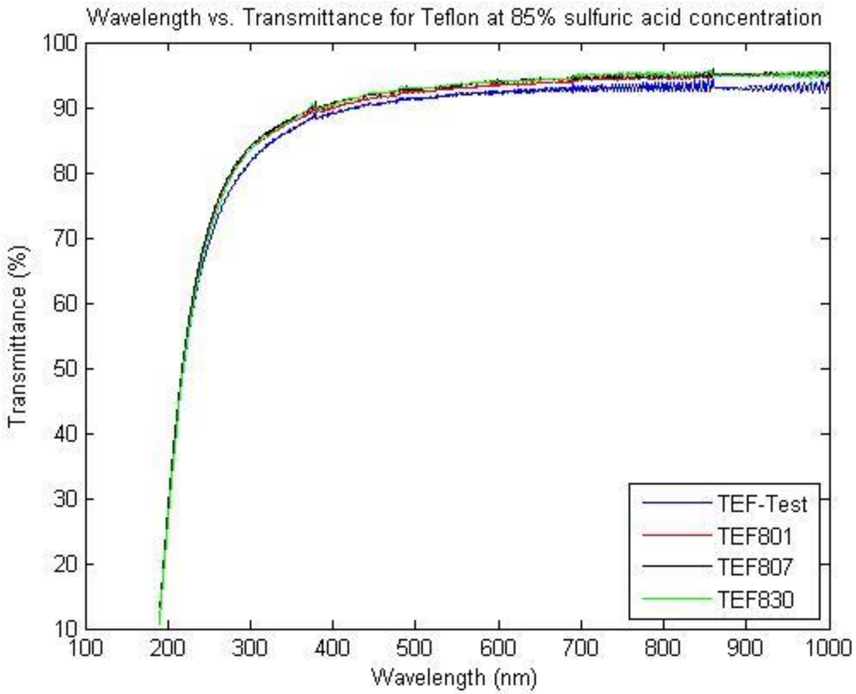


75%: Avg. Transmittance 300 – 1000 nm	
Unexposed	90.7%
1 Day	90.6%
7 Day	90.1%
30 Day	90.5%

85%: Avg. Transmittance 300 – 1000 nm	
Unexposed	90.7%
1 Day	91.1%
7 Day	90.9%
30 Day	91.1%

FEP Teflon Results

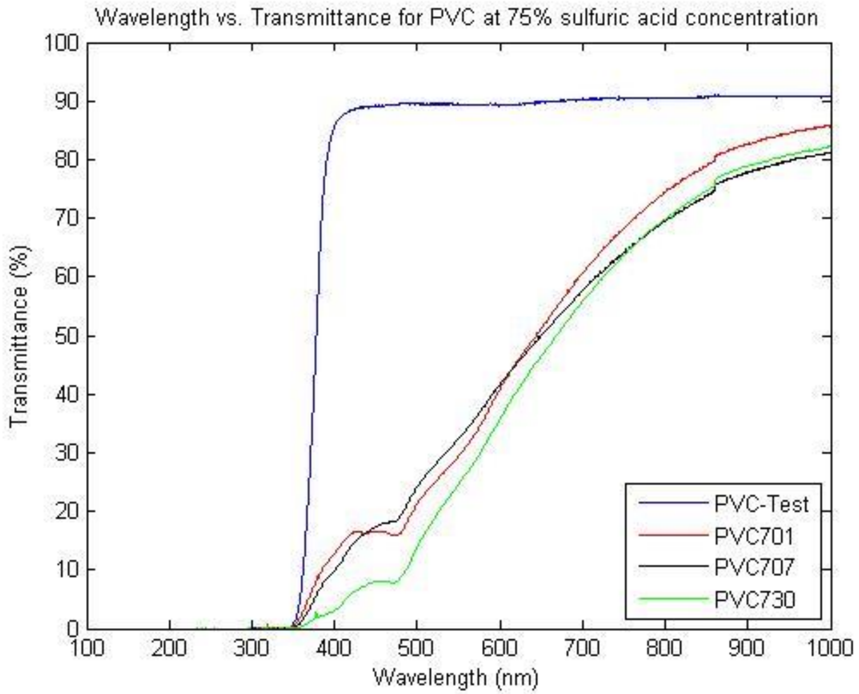


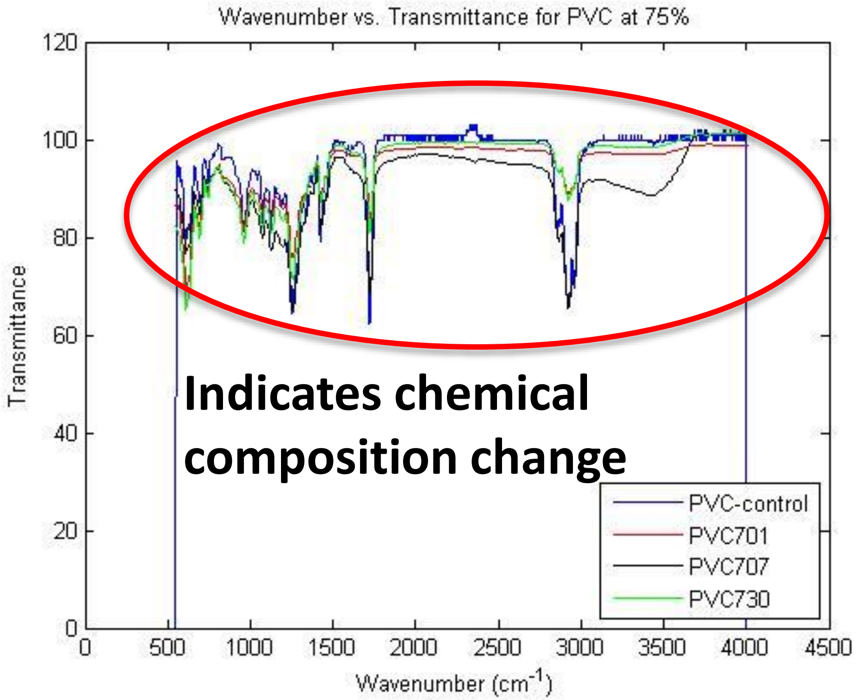


75%: AVG Transmittance 300 – 1000 nm	
Unexposed	91.5%
1 Day	93.1%
7 Day	90.3%
30 Day	92.6%

85%: AVG Transmittance 300 – 1000 nm	
Unexposed	91.5%
1 Day	92.9%
7 Day	92.9%
30 Day	93.2%

Polyvinyl Chloride (PVC) Results





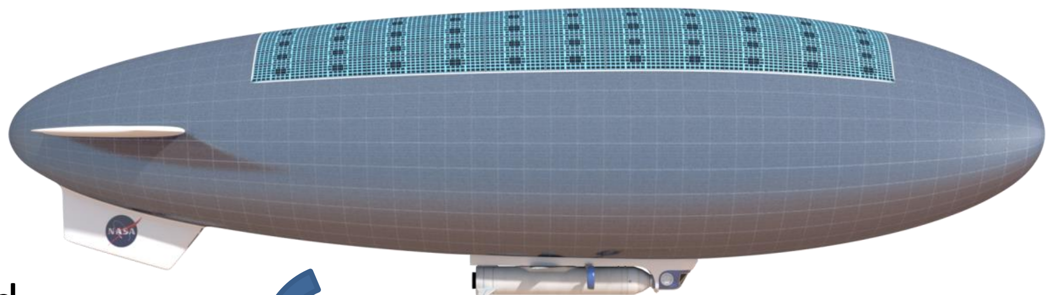
75%: AVG Transmittance 300 – 1000 nm	
Unexposed	80.2%
1 Day	47.6%
7 Day	45.7%
30 Day	42.6%

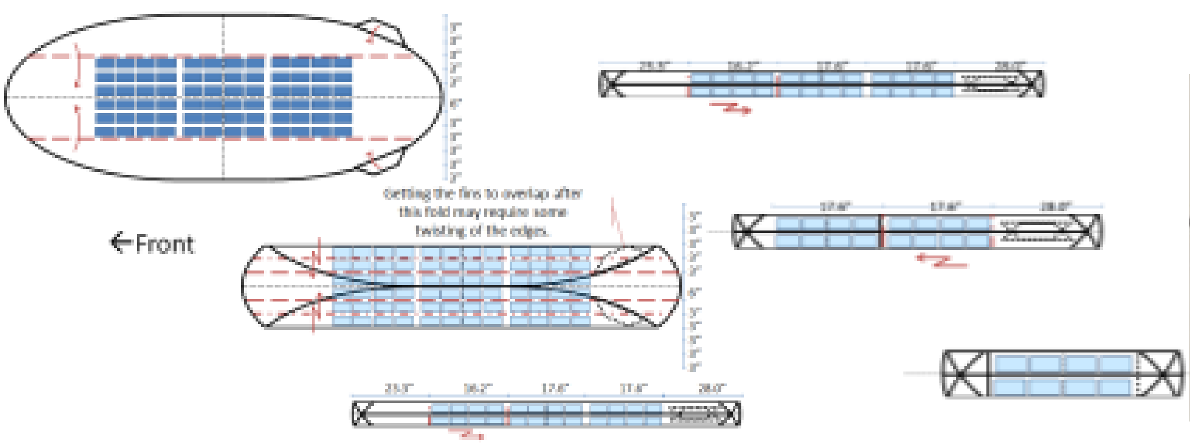
Sulfuric Acid Test Conclusions

- **Polypropylene did not degrade and had 90% transmittance**
  - May degrade when exposed to temperatures above 50°C
- **Teflon did not degrade and had 90-93% transmittance**
  - Highest melting point of tested materials
- **Polyvinyl chloride underwent chemical change and lost transmittance**
  - Fell from 80% to 48% after one day, to 43% after 30 days
- **Teflon and polypropylene recommended for future testing at relevant temperatures (75-80°C)**

Airship Inflation Demonstration

- **Goal:** develop and demonstrate concepts for packaging and Entry, Descent, and Inflation (EDI)
- **Method:** design and construct scale model of HAVOC vehicle, demonstrate that it packages and inflates and document algorithm and concept for future development.

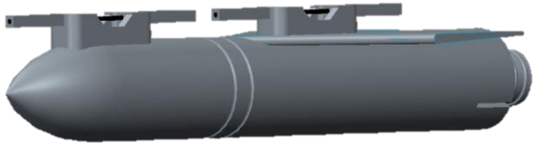




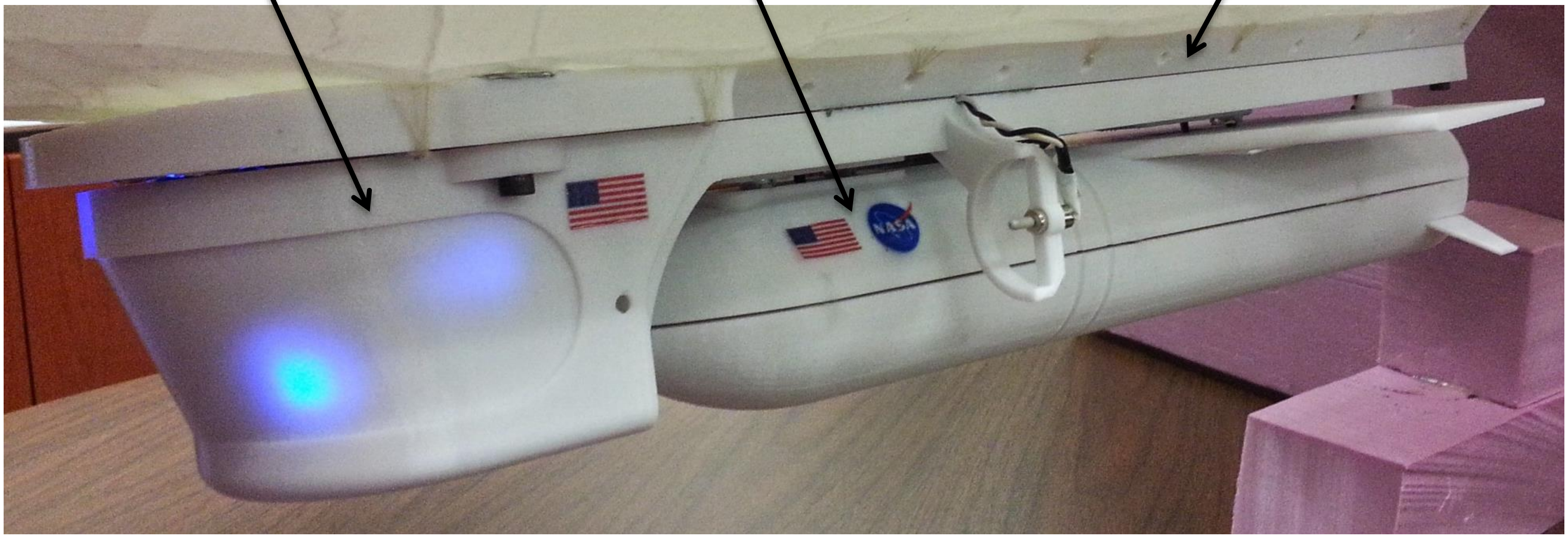
Airship Elements—Gondola

Gondola and Propellers

Ascent Vehicle



Baseplate

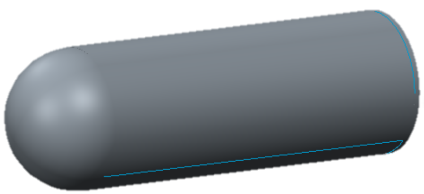


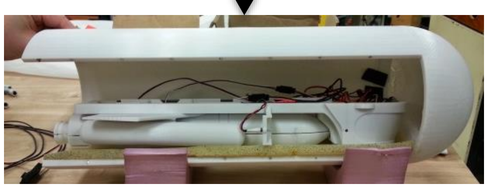
Airship Elements—Structure

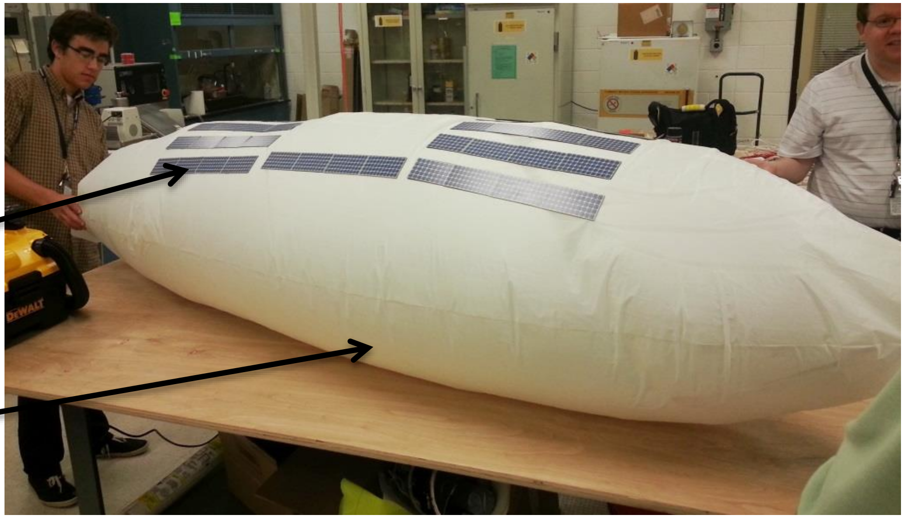
Fins

Gas Bag

Aeroshell



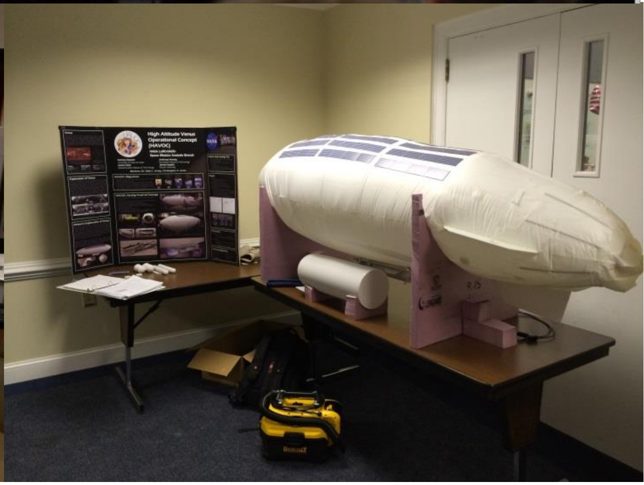




Solar Panels

Envelope

Airship Inflation Demonstrations



Future Questions and Trades

Mission Architecture

- What is the communications architecture for the robotic and human missions?
- What do the Phase 2, Phase 4, and Phase 5 missions look like?
- Detailed design of propulsive stages (TVI/TEI stages, ascent vehicle, etc.)
- Low thrust pre-deployment trade
- Detailed design of science operations for robotic and human missions

Vehicle Concept

- What guidance algorithms yield optimal aerocapture, entry, and ascent trajectories?
- What can be done with the airship after the human mission is complete?
- Refine decelerator, TPS, and deployment/inflation design
- Entry shape, detailed vehicle dynamics, operational simulation, other lifting gases

Proof of Concept

- How do Teflon and polypropylene withstand sulfuric acid at Venus temperatures?
- How does a model of the airship perform in Venus atmospheric conditions?
- Physical tests of inflation on parachute and with tanks

Ascent Habitat Summary

Description

HAVOC Ascent Habitat provides crew habitation for the ascent from the atmosphere of Venus to the orbiting Transit Habitat.

Design Constraints/Parameters

Pressurized Vol.	4.6	m^3
Habitable Vol.	2.6	m^3
Atmospheric Pressure	101.4	kPa
Crew Capacity	2	
Crewed Mission Duration	1	d
EOL Power Required	1	kW
Total battery energy storage	49	kW-h
Number of Batteries	3	
Depth of Discharge	80	%
Power load during battery operati	1.0	kW
ECLSS Closure - Water	Open	
ECLSS Closure - Air	Open	
Habitat Structure	al Rigid Cylinder	
Habitat Length	2.77	m
Habitat Diameter	1.50	m
Mass Growth Allocation	20%	
Project Manager's Reserve	10%	

Category	Vol., m^3
Systems Volume	1.75
Crew Equipment	0.02
Utilization	0.00
Airlock	0.00
Dry Goods Storage	0.02
Water Storage	0.01
Voids	0.27
Total Non-Habitable Volume	2.07
Habitable Volume	2.56
Total Pressurized Volume	4.63

Category	Mass, kg
Structure	523
Protection	21
Propulsion	0
Power	539
Control (ACS/RCS)	0
Avionics	323
ECLSS	128
Air, Thermal, Fire Subsystems	*116*
Water Subsystem	*12*
EVA systems	0
Thermal Control System	117
Crew Equipment	3
Utilization	0
Growth	495
Radiation Protection (waterwall)(Not included in growth)	0
DRY MASS SUBTOTAL	2,150
Logistics	4
Food (including Trays & Wraps)	4
Waste Collection (Fecal Canisters, Urine Prefilters,	0
Personal Hygiene Kit	0
Hygiene Consumables	0
Clothing	0
Recreation & Personal Stowage	0
Wipes /Paper/Tissue (Housekeeping)	0
Trash Bags	0
Operational Supplies	0
Survival Kit	0
Sleep Accomodations	0
Health Care Consumables	0
Emergency Breathing Apparatus	0
Spares	0
Maintenance Items	0
ECLSS Consumables (Nominal + Contingency)	18
Reserve and Residual Prop.	0
INERT MASS SUBTOTAL	2,172
Propellant	0
TOTAL WET MASS	2,172

Atmospheric Habitat Summary

Description

HAVOC Atmospheric Habitat provides habitation for 2 crew for up to 28 days. No EVA support is currently provided. Propellant and power generation are provided by attached elements.

Design Constraints/Parameters

Pressurized Vol.	20.7	m^3
Habitable Vol.	10.8	m^3
Atmospheric Pressure	101.4	kPa
Crew Capacity	2	
Crewed Mission Duration	28	d
EOL Power Required	3	kW
Total battery energy storage	6	kW-h
Number of Batteries	3	
Depth of Discharge	80	%
Power load during battery operati	2.4	kW
ECLSS Closure - Water	Open	
ECLSS Closure - Air	Open	
Habitat Structure	al Rigid Cylinder	
Habitat Length	3.41	m
Habitat Diameter	2.91	m
Mass Growth Allocation	20%	
Project Manager's Reserve	10%	

Category	Vol, m^3
Systems Volume	3.4
Crew Equipment	1.4
Utilization	0.0
Airlock	0.0
Dry Goods Storage	3.6
Water Storage	0.2
Voids	1.3
Total Non-Habitable Volume	9.9
Habitable Volume	10.8
Total Pressurized Volume	20.7

Category	Mass, kg
Structure	**1,104**
Protection	**54**
Propulsion	**0**
Power	**412**
Control (ACS/RCS)	**0**
Avionics	**441**
ECLSS	**607**
Air Subsystem	*250*
Water Subsystem	*84*
Food Processing	*36*
Human Accommodations	*0*
Other	*237*
EVA systems	**0**
Thermal Control System	**214**
Crew Equipment	**286**
Utilization	**0**
Growth	**892**
Radiation Protection (waterwall)(Not Included in growth)	**0**
DRY MASS SUBTOTAL	**4,011**
Logistics	**857**
Food (Including Trays & Wraps)	103
Waste Collection (Fecal Canisters, Urine Prefilters,	9
Personal Hygiene Kit	4
Hygiene Consumables	4
Clothing	8
Recreation & Personal Stowage	0
Wipes /Paper/Tissue (Housekeeping)	11
Trash Bags	3
Operational Supplies	40
Survival Kit	0
Sleep Accomodations	18
Health Care Consumables	40
Emergency Breathing Apparatus	3
Spares and Maintenance Items	512
CTBs	103
ECLSS Consumables (Nominal + Contingency)	**216**
Reserve and Residual Prop.	**0**
INERT MASS SUBTOTAL	**5,085**
Propellant	**0**
TOTAL WET MASS	**5,085**

Transit Habitat Summary

Description

HAVOC Transit Habitat provides crew habitation with for long-duration transit to and from Venus. It includes an internal Shuttle-class airlock for contingency EVAs and generates its own power.

Design Constraints/Parameters

Pressurized Vol.	100.3	m^3
Habitable Vol.	44.0	m^3
Atmospheric Pressure	101.4	kPa
Crew Capacity	2	
Crewed Mission Duration	410	d
EOL Power Required	12	kW
Total battery energy storage	22	kW-h
Number of Batteries	3	
Depth of Discharge	80	%
Power load during battery operati	9.1	kW
ECLSS Closure - Water	Partially Closed	
ECLSS Closure - Air	Partially Closed	
Habitat Structure	al Rigid Cylinder	
Habitat Height	4.33	m
Habitat Diameter	5.86	m
Mass Growth Allocation	20%	
Project Manager's Reserve	10%	

Category	Vol., m^3
Systems Volume	7.9
Crew Equipment	9.4
Utilization	0.0
Airlock	6.0
Dry Goods Storage	26.2
Water Storage	0.3
Voids	6.5
Total Non-Habitable Volume	56.3
Habitable Volume	44.0
Total Pressurized Volume	100.3

Category	Mass, kg
Structure	2,767
Protection	162
Propulsion	0
Power	861
Control (ACS/RCS)	0
Avionics	453
ECLSS	2,341
Air Subsystem	*834*
Water Subsystem	*1,033*
Food Processing	*36*
Human Accommodations	*84*
Other	*353*
EVA systems	1,477
Thermal Control System	660
Crew Equipment	1,688
Utilization	0
Growth	3,002
Radiation Protection (waterwall)(Not included in growth)	0
DRY MASS SUBTOTAL	13,412
Logistics	6,290
Food (Including Trays & Wraps)	1,444
Waste Collection (Fecal Canisters, Urine Prefilters,	651
Personal Hygiene Kit	4
Hygiene Consumables	70
Clothing	35
Recreation & Personal Stowage	50
Wipes /Paper/Tissue (Housekeeping)	171
Trash Bags	44
Operational Supplies	40
Survival Kit	0
Sleep Accomodations	18
Health Care Consumables	88
Emergency Breathing Apparatus	0
Spares	2,686
Maintenance Items	246
CTBs	744
ECLSS Consumables (Nominal + Contingency)	448
Reserve and Residual Prop.	0
INERT MASS SUBTOTAL	20,151
Propellant	0
TOTAL WET MASS	20,151

Ascent Habitat Assumptions

BASELINE ASSUMPTIONS

Structure and Mechanisms

Metallic, cylindrical habitat: 1.28 m^3 habitable volume per person

Min.2.5 m barrel length for reasonable ceiling height

~22 m^3/person habitable volume

Secondary structure 2.46 km/m^2 of habitat surface area

Launch integration 2% of habitat gross mass

1 - 0.5 m diameter window

1 docking mechanism, 0 docking tunnels

Atmospheric pressure = 101.3 kPa (14.7 psi)

Avionics

Provide CC&DH, GN&C, communication

Thermal Control

External fluid loop using Ammonia

Internal fluid loop using 60% prop glycol/water

Xx kW heat rejection using ISS-type radiators

Maintenance and Spares

No spares manifested

Reserves

Margin Growth Allowance: 20% of basic mass

Project Manager's Reserve: 10% of basic mass

Protection

20 layers multi-layer insulation

Power

120 V DC power management (92% efficient)

3 Li-ion batteries (200 W-hr/kg) where any 2 provide 1 kW for 24 hours

Environmental Control and Life Support

Open loop consumables and air distribution hardware only

Modeled with Envision ECLSS model

Crew Equipment & Accommodations

Food, lighting, and hygiene items only.

Extra-Vehicular Activity (EVA)

No EVA capability

Atmospheric Habitat Assumptions

BASELINE ASSUMPTIONS

Structure and Mechanisms

Metallic, 3m cylindrical habitat: 5.4 m^3 habitable volume per person

Min.2.5 m barrel length for reasonable ceiling height

Secondary structure 2.46 km/m^2 of habitat surf area

Launch integration 2% of habitat gross mass

Four 0.5 m diameter windows

1 exterior hatch

1 docking mechanisms, 1 docking tunnels

Atmospheric pressure = 101.3 kPa (14.7 psi)

Avionics

Provide CC&DH, GN&C, communications

Thermal Control

External fluid loop using Ammonia

Internal fluid loop using 60% prop glycol/water

Xx kW heat rejection using ISS-type radiators

Maintenance and Spares

Sized using Monte Carlo simulation engine (EMAT)

Reserves

Margin Growth Allowance: 20% of basic mass

Project Manager's Reserve: 10% of basic mass

Protection

20 layers multi-layer insulation

5.8 cm water-wall on crew quarters for SPE protection

Power

~XX kWe end of life power provided by external power system

120 V DC power management (92% efficient)

3 Li-ion batteries (200 W-hr/kg) ~XX kW-hr storage

Environmental Control and Life Support

Open Loop ECLSS, LIOH CO2 Removal, Water Storage, O2 and H2O Storage

10% mass for advanced diagnostics and maintainability

30 days open loop contingency consumables

Crew Equipment & Accommodations

Standard suite for 0-31 day missions

Crew items, sink (spigot), food warmer, toilet

vacuums, seats, medical kit, wipes, photography equiment

Logistics

Sized based upon ISS usage rates

Extra-Vehicular Activity (EVA)

No EVA capability provided

Transit Habitat Assumptions

BASELINE ASSUMPTIONS

Structure and Mechanisms
- Metallic, cylindrical habitat: max 7.2 m diameter
- 0.3 m for port extrusions, attachments, structure
- Min.2.5 m barrel length for reasonable ceiling height
- ~22 m^3/person habitable volume
- Secondary structure 2.46 km/m^2 of habitat surf area
- Launch integration 2% of habitat gross mass
- Four 0.5 m diameter windows
- 1 exterior hatch
- 2 docking mechanisms, 2 docking tunnels
- Atmospheric pressure = 70.3 kPa (10.2 psi)

Avionics
- Provide CC&DH, GN&C, communications

Thermal Control
- External fluid loop using Ammonia
- Internal fluid loop using 60% prop glycol/water
- TBD kW heat rejection using ISS-type radiators

Maintenance and Spares
- Sized using Monte Carlo simulation engine (EMAT)

Reserves
- Margin Growth Allowance: 20% of basic mass
- Project Manager's Reserve: 10% of basic mass

Protection
- 20 layers multi-layer insulation

Power
- ~XX kWe end of life power 3-Junction GaAs arrays sized for Earth
- 120 V DC power management (92% efficient)
- 3 Li-ion batteries (200 W-hr/kg) ~XX kW-hr storage

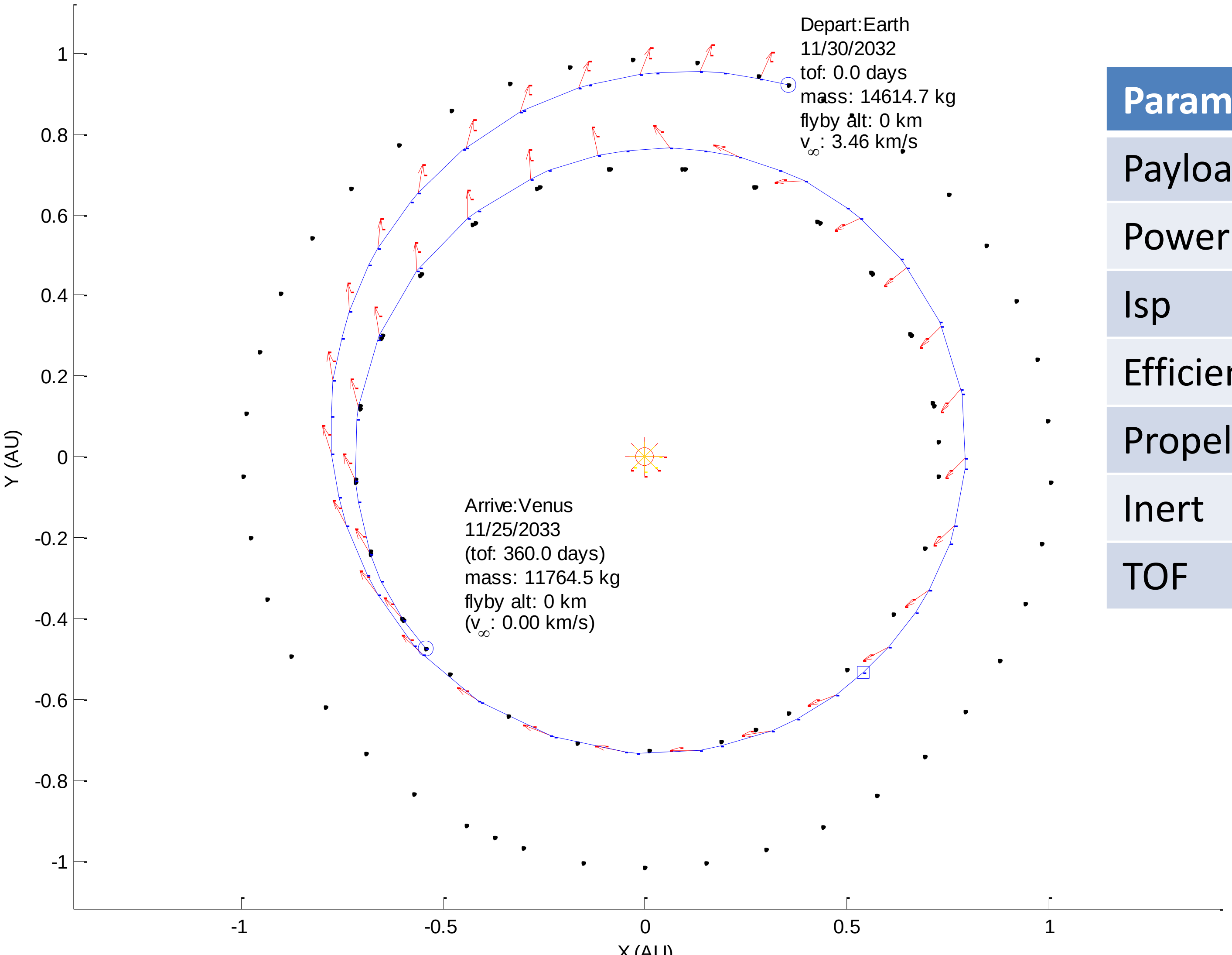
Environmental Control and Life Support
- Scaled ISS level ECLSS (100% air, ~85% water) hardware for 380 days
- 10% mass for advanced diagnostics and maintainability
- 30 days open loop contingency consumables

Crew Equipment & Accommodations
- Standard suite for 180-360 day deep-space
- Assume freezer for missions longer than 1-year
- Crew items, sink (spigot), freezer, microwave, washer, dryer, 2 vacuums, laptop, trash compactor, printer, hand tools, test equipment, ergometer, photography, exercise, treadmill, table

Logistics
- Sized based upon ISS usage rates + 30 days contingency

Extra-Vehicular Activity (EVA)
- 600 kg 6 m^3 internal airlock for contingency
- 2 person EVAs using shuttle-class internal airlock
- 1 spare per suit for every suit component
- 1 EVA per 30 days

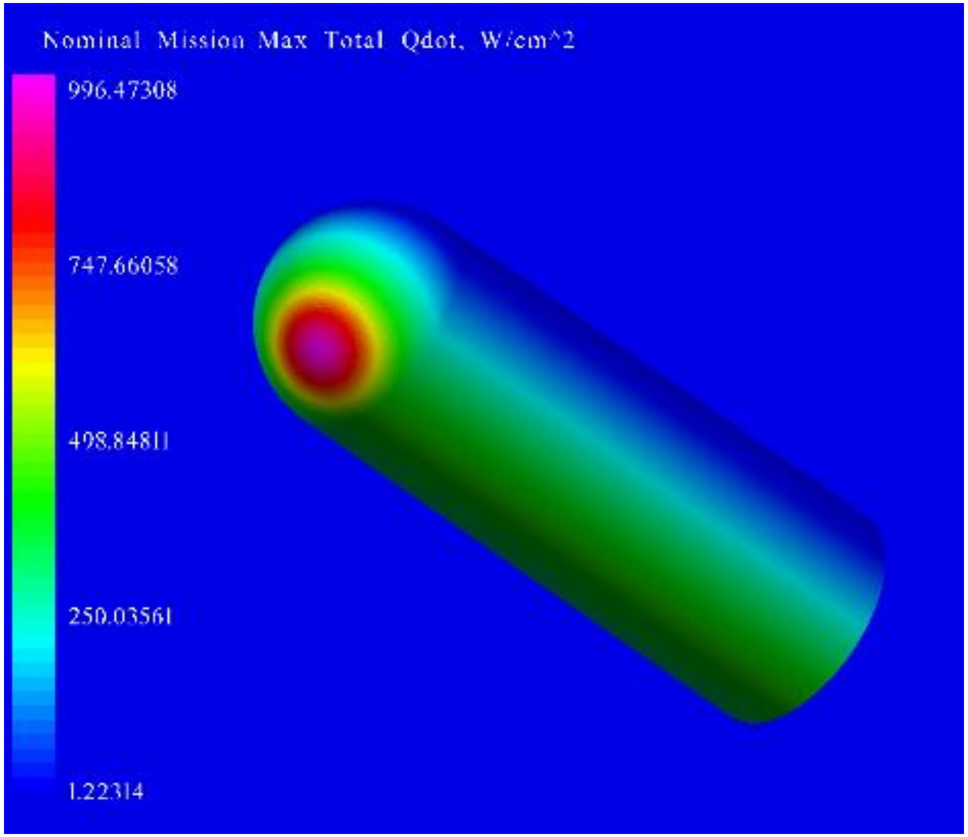
Low Thrust One-Way to Venus – Notional



Parameter	Value
Payload	3000 kg
Power	50 kWe
Isp	2500 s
Efficiency	60%
Propellant	2850 kg
Inert	8770 kg
TOF	360 days

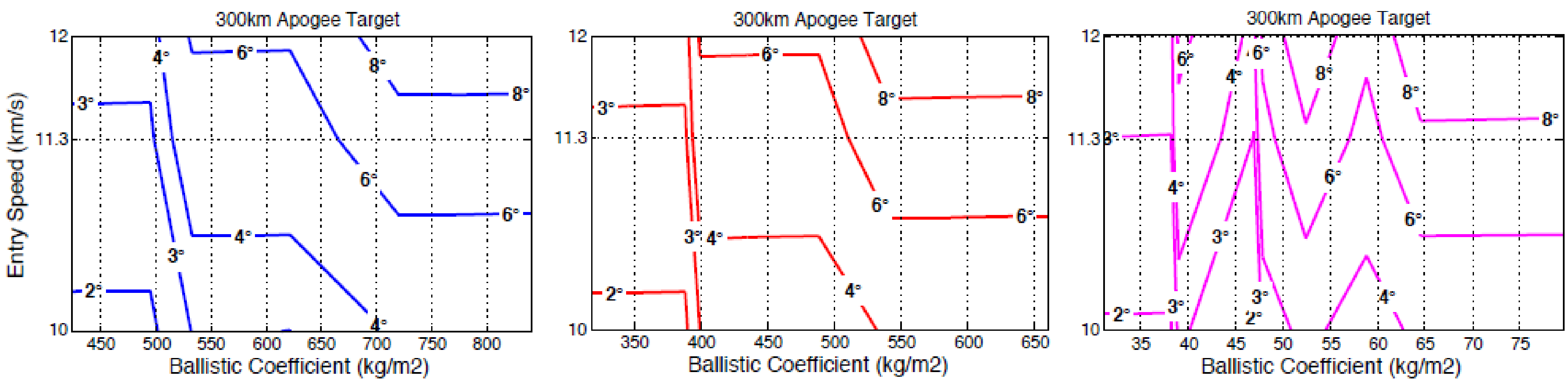
Aerothermodynamics

- **Entry vehicle modeled as ellipsled design from EDLSA study**
  - Right circular cylinder
  - Hemispherical nose cap & flat base
  - Total length-to-diameter ratio of 3
- **Databases for 4.7 m (unmanned robotic precursor) and 10 m (manned) diameter ellipsleds generated with CBAERO**
- **Tables include static aero coefficients, convective & radiative heat rates**
- **For conservative aeroheating, fully turbulent flow and fully catalytic wall**
  - Mach 24 point check case matched LAURA stagnation point heating
- **Databases span dimensions of Mach, dynamic pressure, and angle of attack**
  - M_∞: 1.5 to 50
  - q_∞: 1.E-8 to 6.E-2 bar
  - α_T: 0 to 90 degrees



Aerocapture Entry Flight Path Corridor

Human Mission - Cargo | **Human Mission - Crewed** | **Robotic Mission**

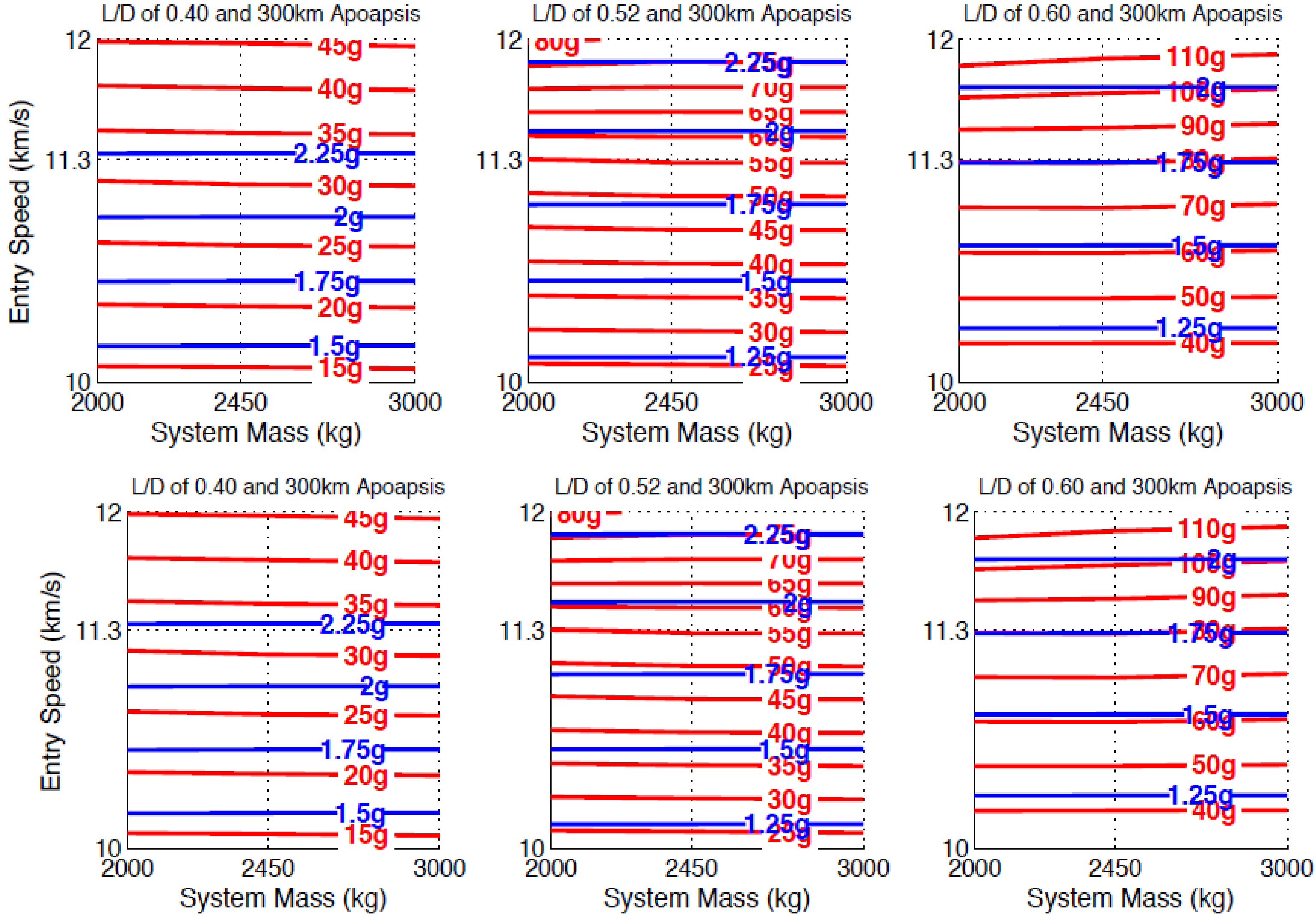


- **Past studies at Venus have shown that roughly 1 degree of entry flight path angle corridor width is necessary to fly out any unexpected dispersions during aerocapture. All of these cases posses well above 1 degree of corridor width and are therefore deemed viablecases.**

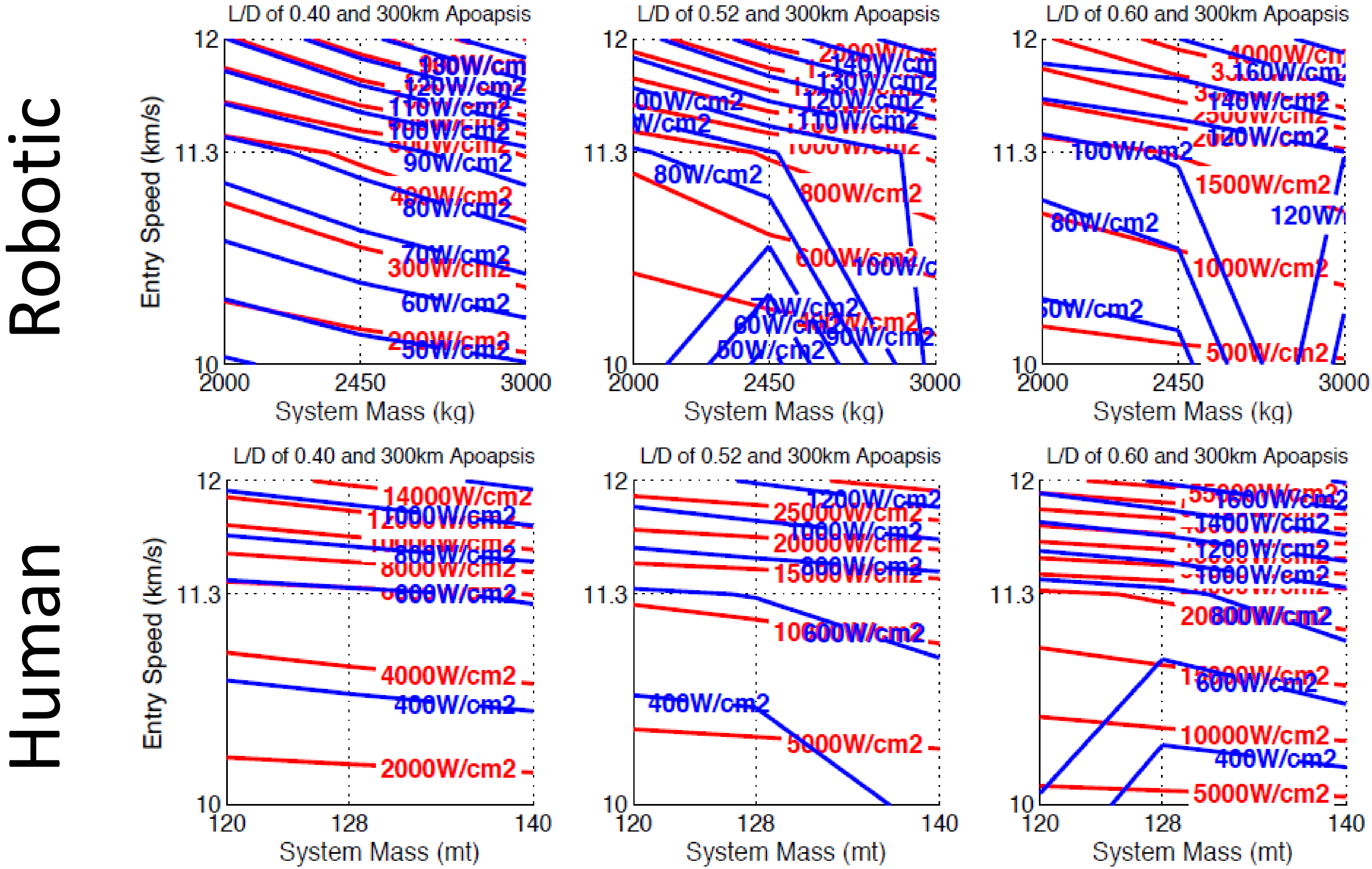
Aerocapture Acceleration

Robotic

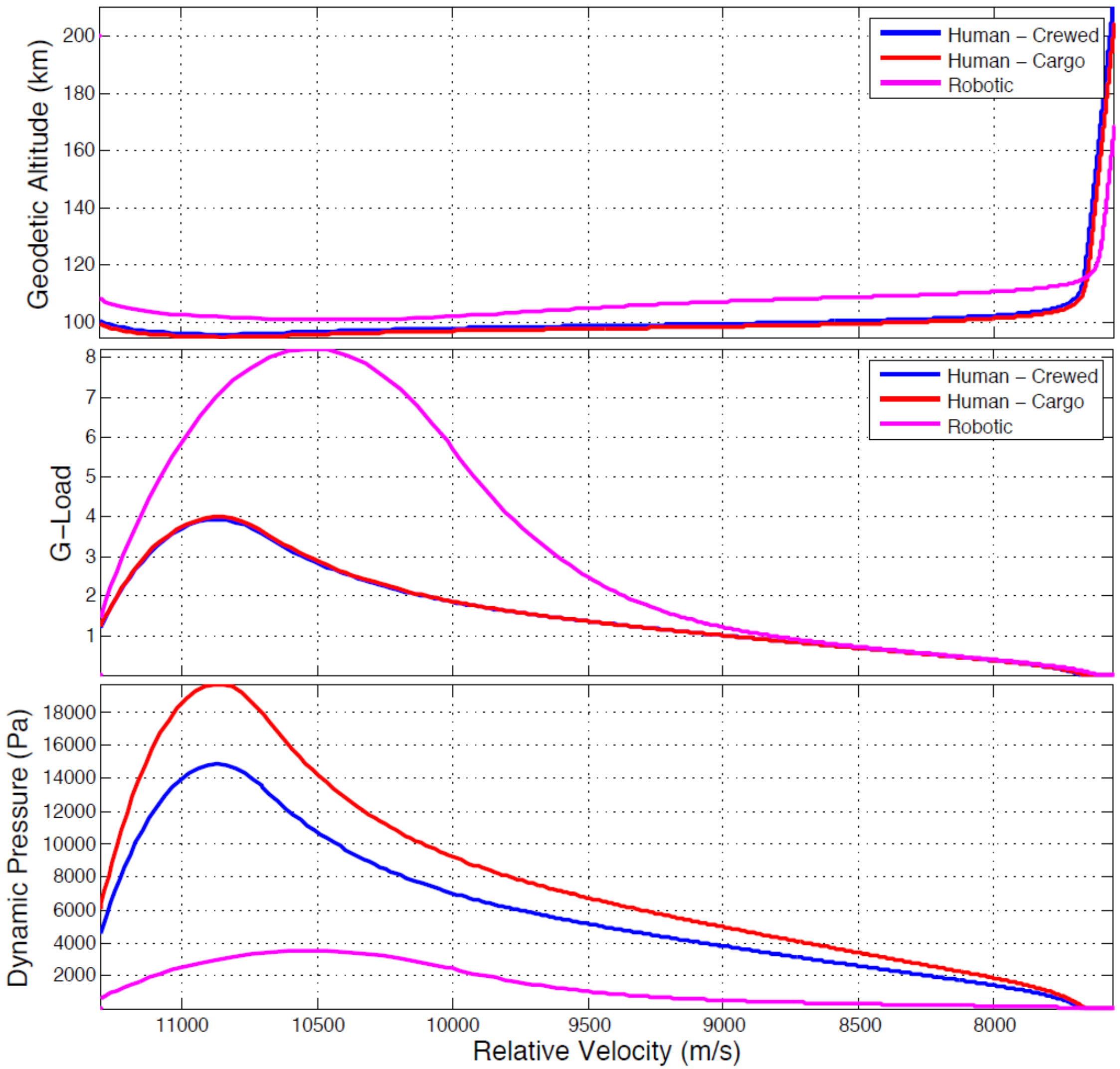
Human



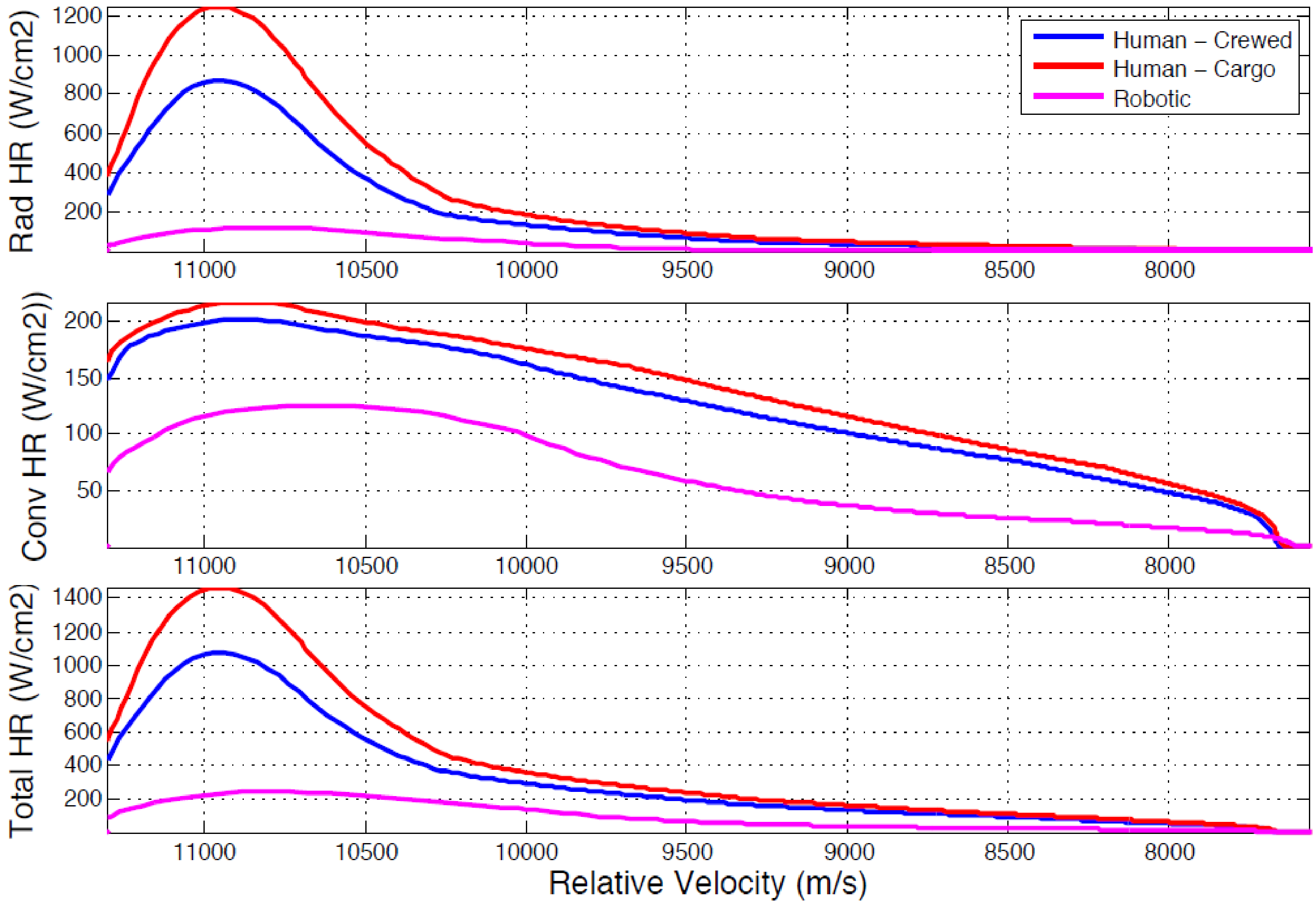
Aerocapture Heat Rate



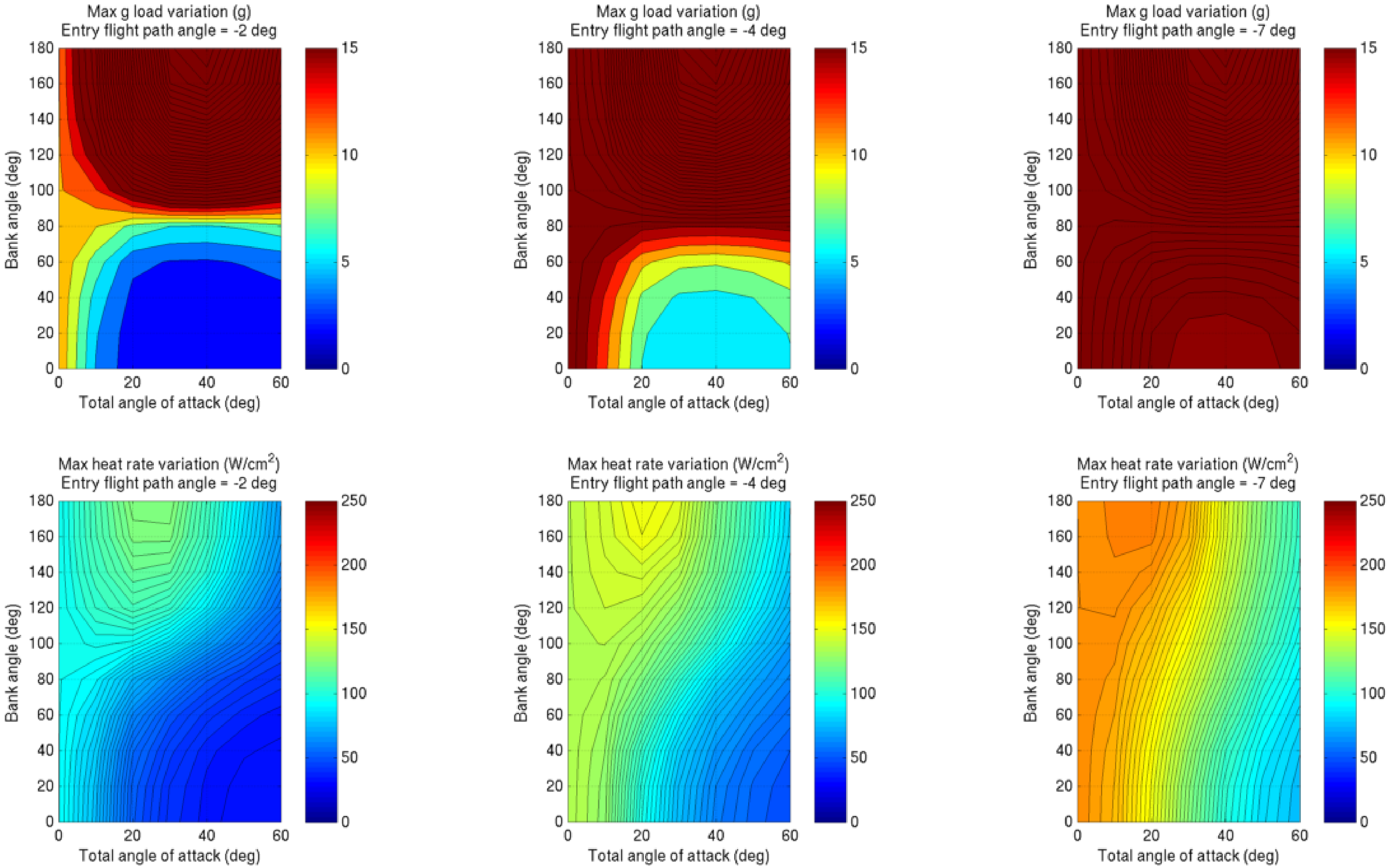
Aerocapture Trajectory



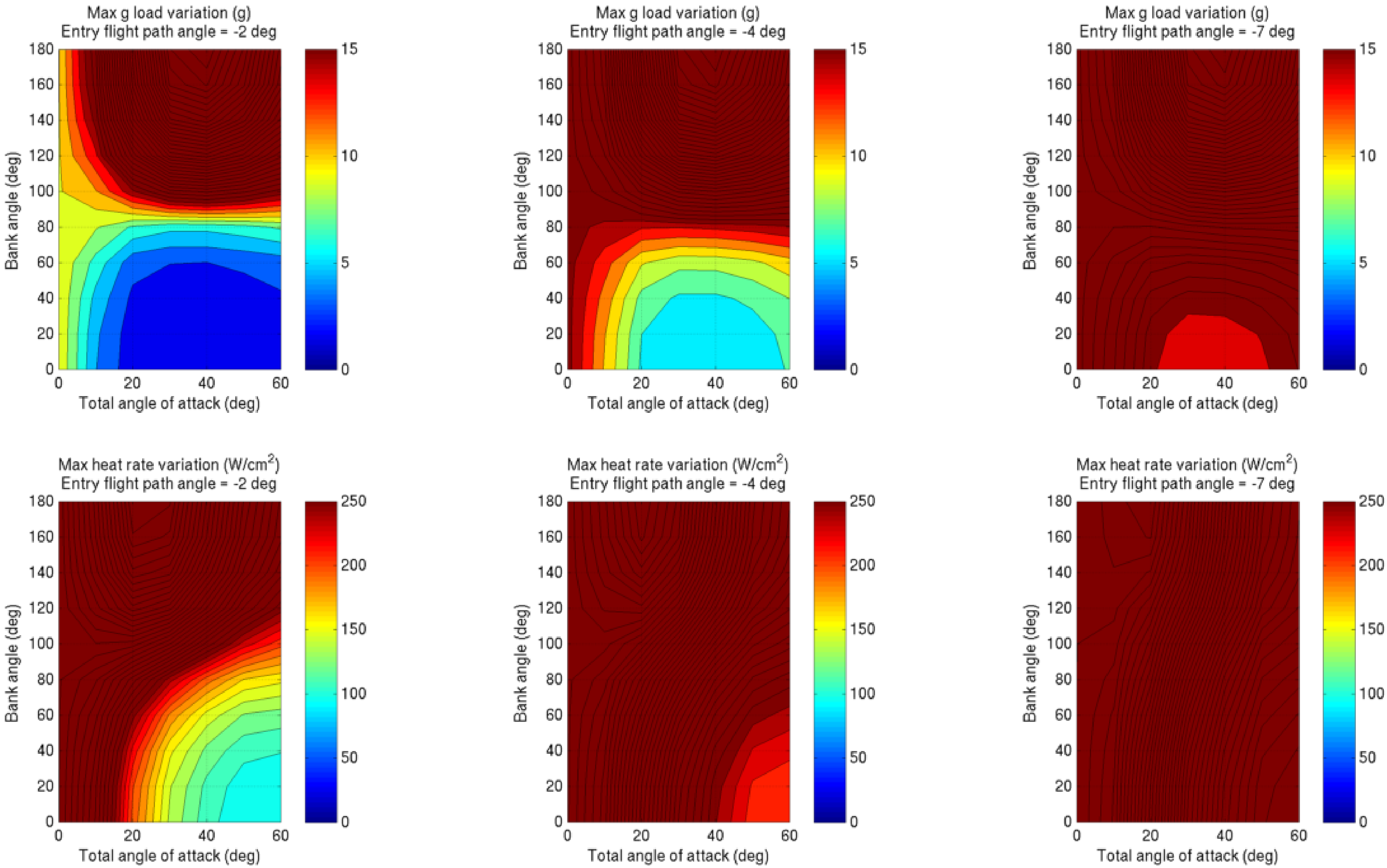
Aerocapture Heating Loads



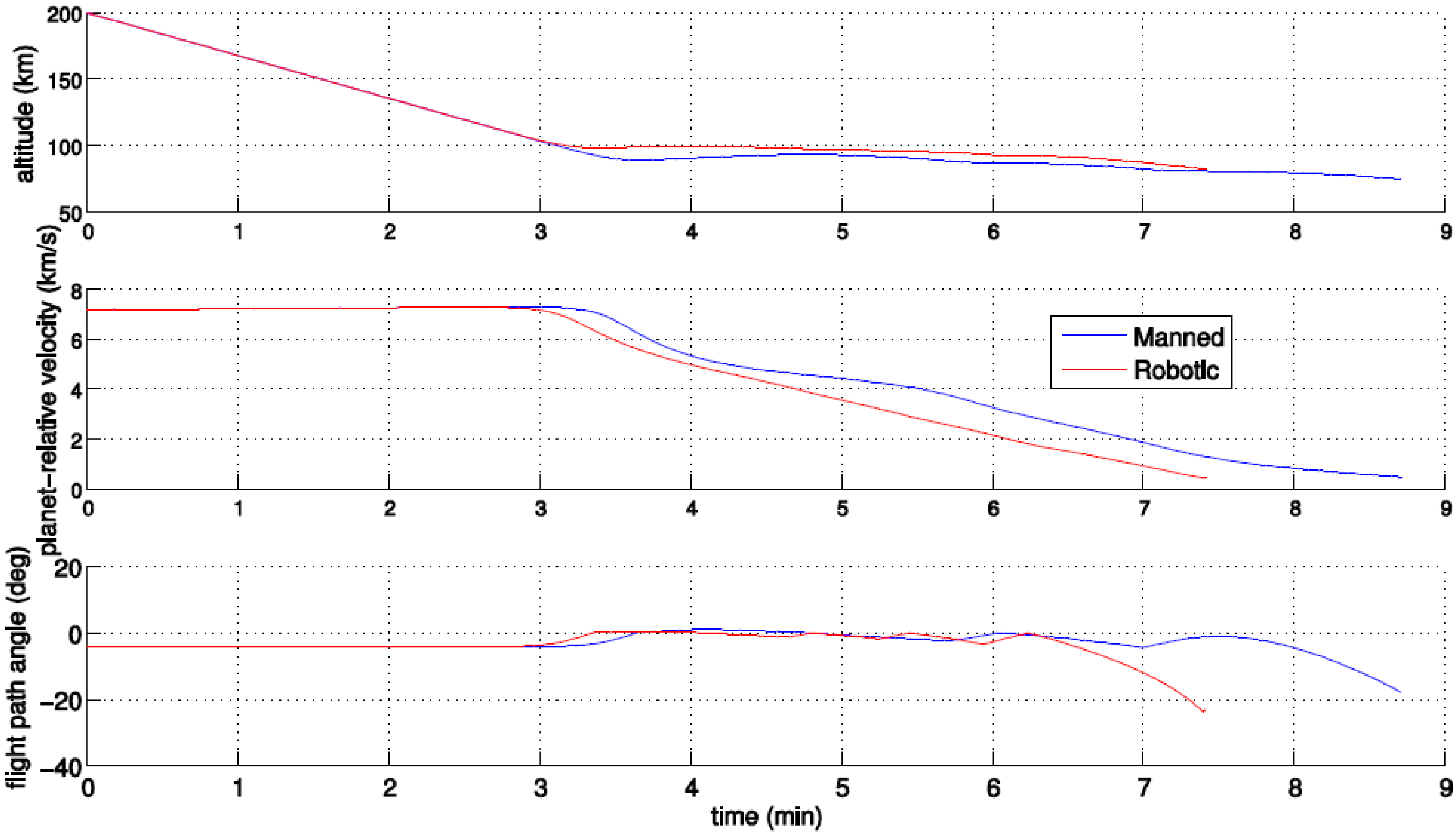
Robotic Mission Entry Trajectory Design Space



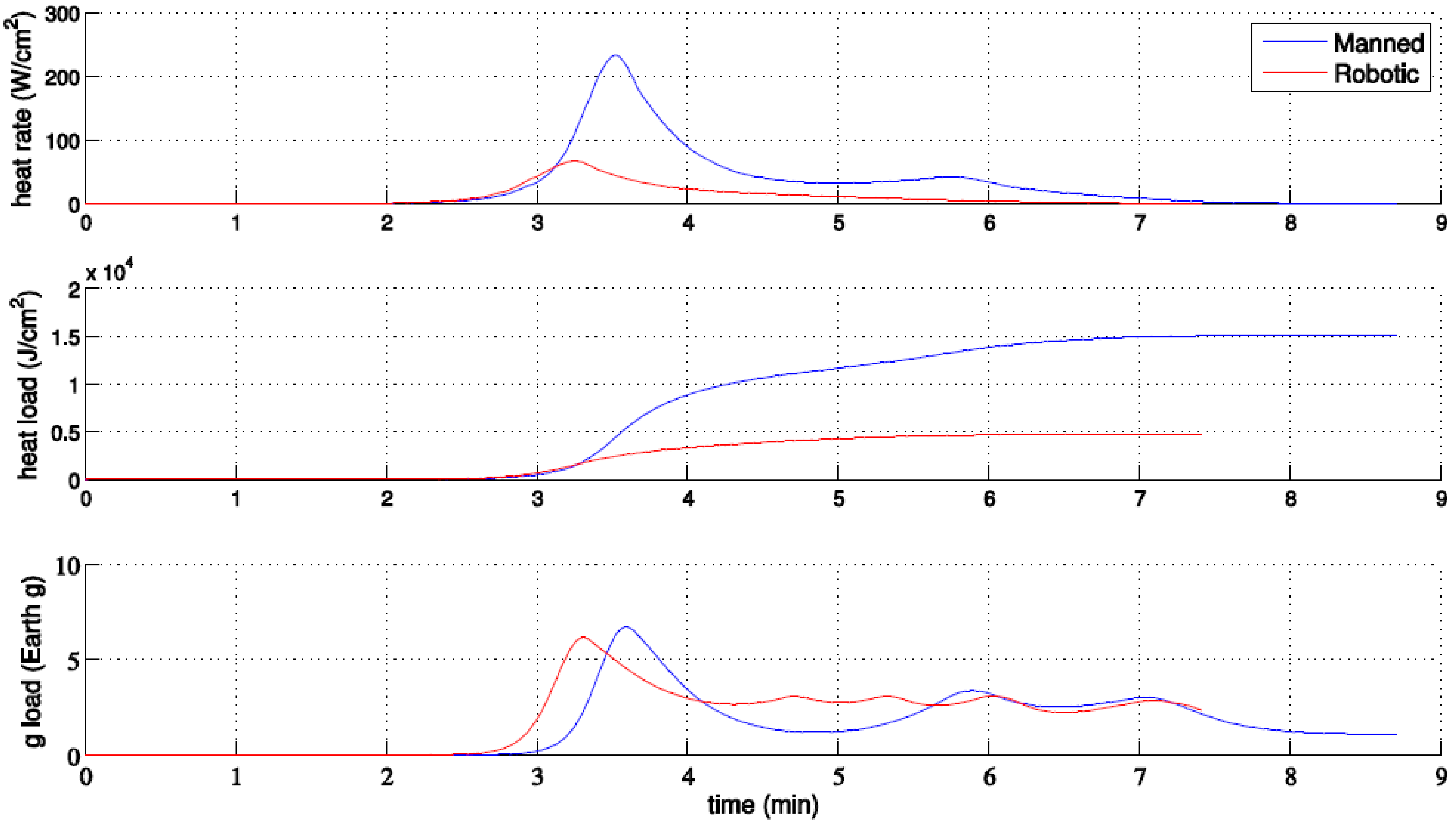
Human Mission Entry Trajectory Design Space



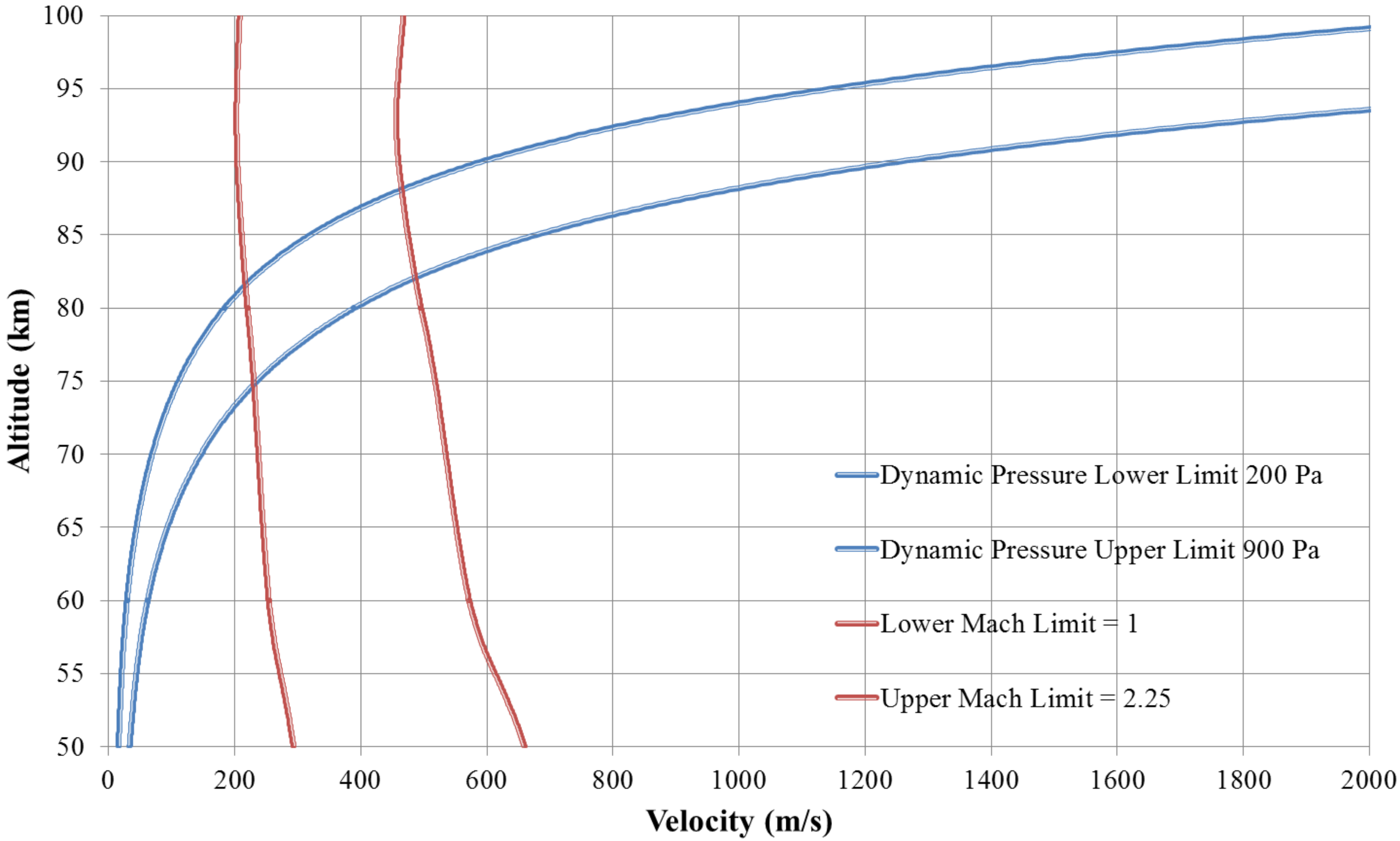
Overview of Selected Trajectories



Aero Loads for Selected Entry Trajectories



Historical Disc Gap Band Parachute Deploy Conditions

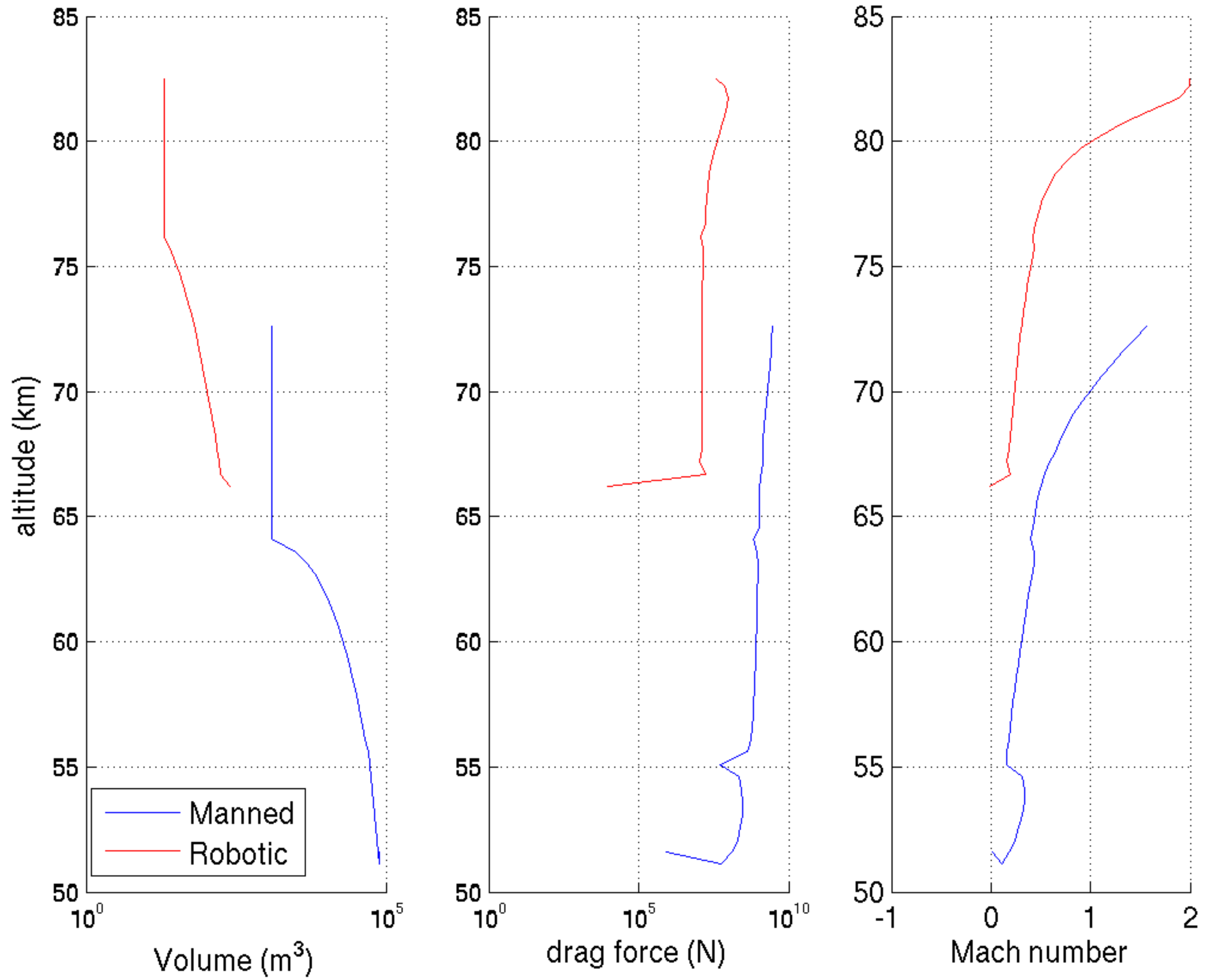


Airship Inflation Modeling

- **Manned mission unable to reach low enough dynamic pressure to deploy conventional supersonic parachute**
  - Continue analysis by assuming there is technology available (e.g., ballute, IAD, etc.) that permits a decelerator deployment at high dynamic pressures (3-4 kPa)
- **Terminal Descent Model (TDM) developed to analyze how aerodynamic, buoyancy, and inertial forces combine to adjust terminal velocity during unpowered descent**
  - TDM determines aerodynamic and buoyancy forces acting on vehicle configuration as function of time at altitude increments of 500 m
  - Distinct modeling and calculations applied to each phase of descent due to characteristically different vehicle configurations, weights, and buoyancy forces
- **Assumptions: All terminal descent operations occur under parachute**
  - Atmosphere molecular weight of 43.58 g/mole (97% CO_2, 3% N_2) & helium lifting gas weight of 4.0 g/mole
  - Multiple tanks are used in sequence and jettisoned when depleted
  - Airship inflation begins & aeroshell jettisoned when velocity is 100 m/s
  - Parachute jettisoned when buoyancy to parachute drag ratio exceeds 90%

Airship Inflation Results

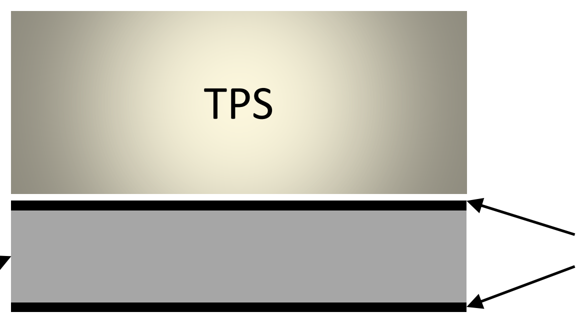
- **Airship inflation begins at $V_{\infty} = 100$ m/s**
  - Constant inflation rate
- **“Kinks” in drag force profile due to jettison of aeroshell and parachute**
- **Corresponding sudden increases in Mach number**
- **Altitude at full inflation higher than 50 km**
  - Designed neutral buoyancy point will bring airship to 50 km



Thermal Protection Materials Selection

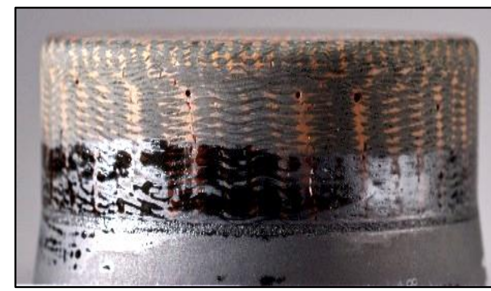
- **Thermal Protection System (TPS) Candidates**
  - **HEEET (Heatshield for Extreme Entry Environment Technology):** dual layer material, high density outer "recession" layer woven in the through thickness direction to a lower density "insulation" layer, 3D woven carbon fibers infused with phenolic resin
  - **PICA (Phenolic Impregnated Carbon Ablator):** monolithic resin infused fiber-form insulation

PICA



0.1 cm Graphite/BMI facesheets

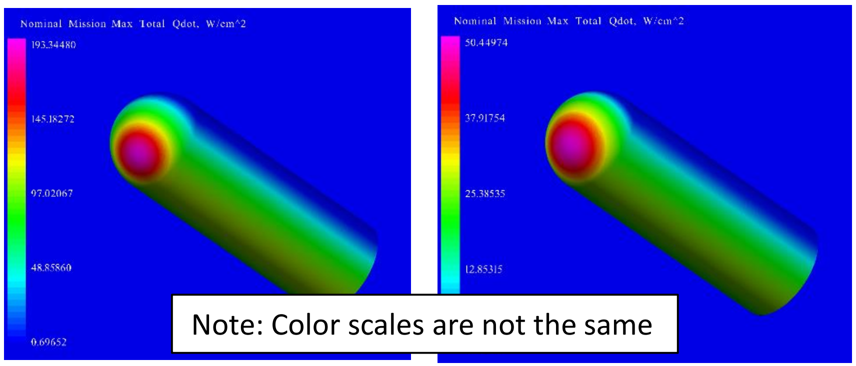
5.08 cm, 70 kg/m^3
Aluminum honeycomb



HEEET

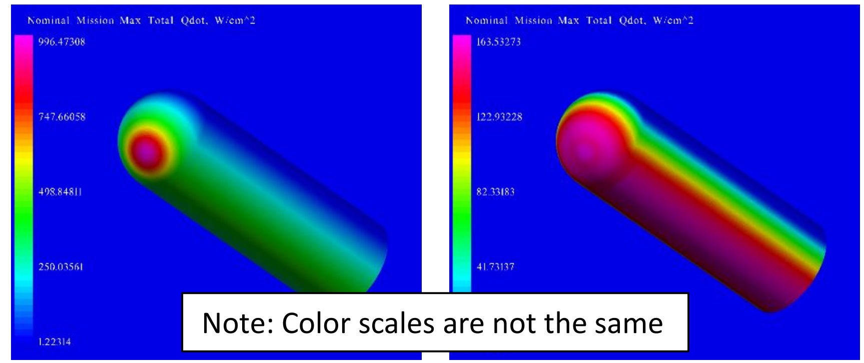
TPS Tailoring Overview

Robotic Heat Flux Distribution

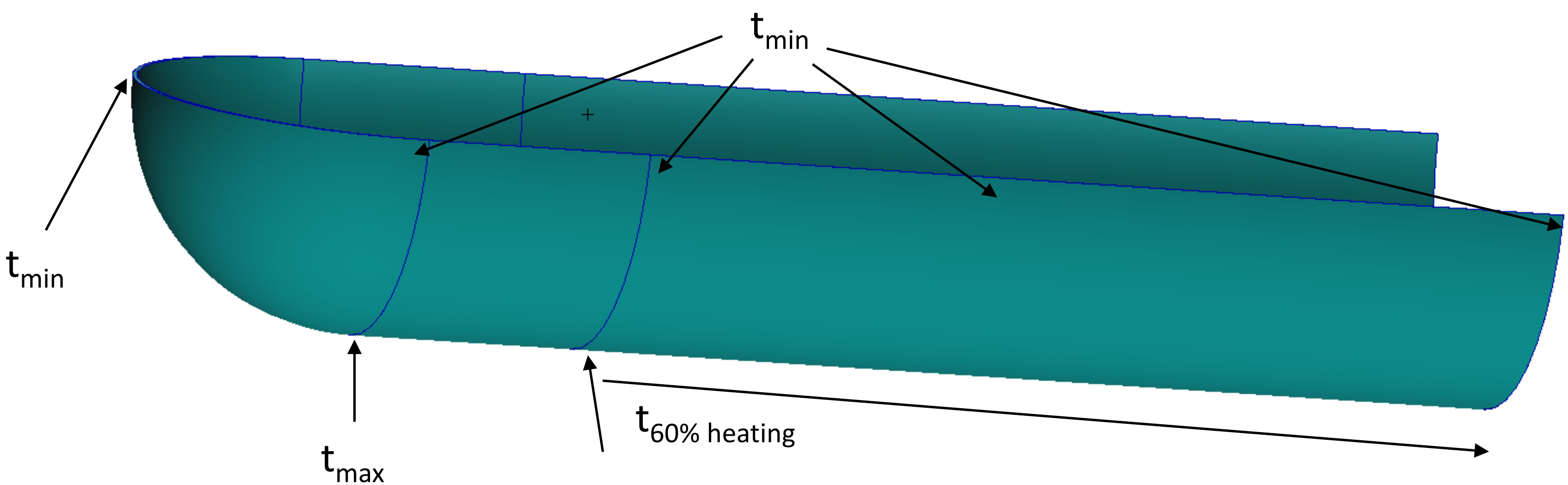


Aerocapture Entry

Human Heat Flux Distribution



Aerocapture Entry



TPS Results Summary

- **TPS Tailoring**
  - No TPS required on back side of the sphere or cylinder sections
  - Maximum thickness at the intersection of the sphere and cylinder at the centerline
  - Longitudinally: Thickness falls from t_{max} to 60% of t_{max} down the cylinder along the centerline
  - Circumferentially: Thickness drops from the centerline thickness to minimum thickness (t_{min}) in the circumferential direction
  - Minimum thickness that can be manufactured is assumed to be 5 mm

- **Robotic Mission**
  - PICA selected because it is the lower mass option

- **Human Mission**
  - HEEET selected because PICA is approaching its heat flux limit
  - Could look at multi-material heat shield using HEEET and PICA to save mass
  - Human mission has less flexibility in tailoring

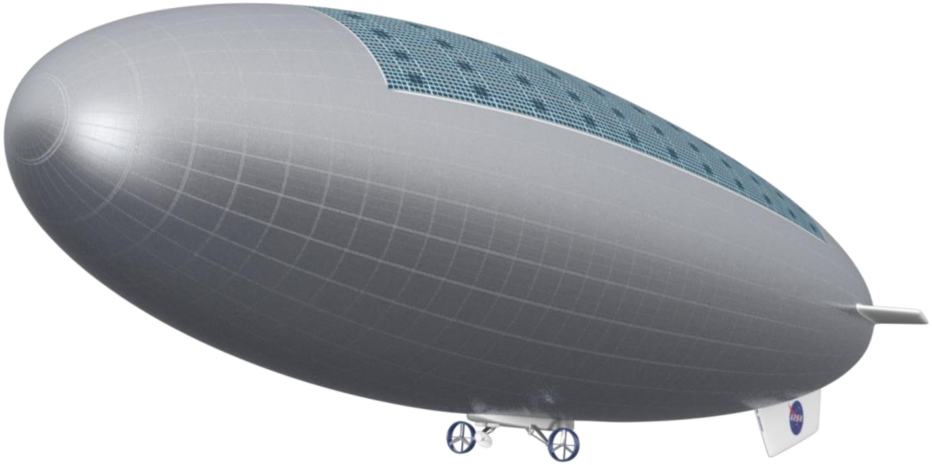
- **The dual pulse capability must be verified for either material**

Mission	Assumed Mass (kg)	Calculated Mass* (kg)
Robotic – PICA	1,050	2,360
Manned – HEEET	33,300	34,500

*25% mass margin

Robotic Mission Mass Summary

Element	Mass (kg)
Payload and Instruments	750
Airship	652
EDI and Aerocapture	1,049
Cruise Stage	122
Trans-Venus Injection Stage	4,604
IMLEO	**7,157**



Human Mission Mass Summary

Element	Mass (kg)
Atmospheric Habitat	5,085
Ascent Habitat	2,172
Ascent Vehicle	62,743
Airship	25,772
EDI and Aerocapture	33,278
Trans-Venus Injection Stage 2	109,351
Trans-Venus Injection Stage 1	109,351
IMLEO	**348,455**

Element	Mass (kg)
Transit Habitat	20,151
Trans-Earth Injection Stage	52,367
Aerocapture	26,496
Trans-Venus Injection Stage 2	63,348
Trans-Venus Injection Stage 1	103,877
IMLEO	**266,238**