Thermal Considerations for 2039 Opposition Class Nuclear Electric Propulsion/Chemical Propulsion Crewed Mars Mission

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Agenda

Modular Assembled Radiators for Nuclear Electric Propulsion (NEP) VehicLes (MARVL)

1. **MARVL Project Background**

2. **Motivation for Thermal Environment Study**

3. **Study Objectives**

4. **Analysis Methods**

5. **Results and Discussion**

6. **Next Steps for Future Work**

7. **Concluding Remarks**
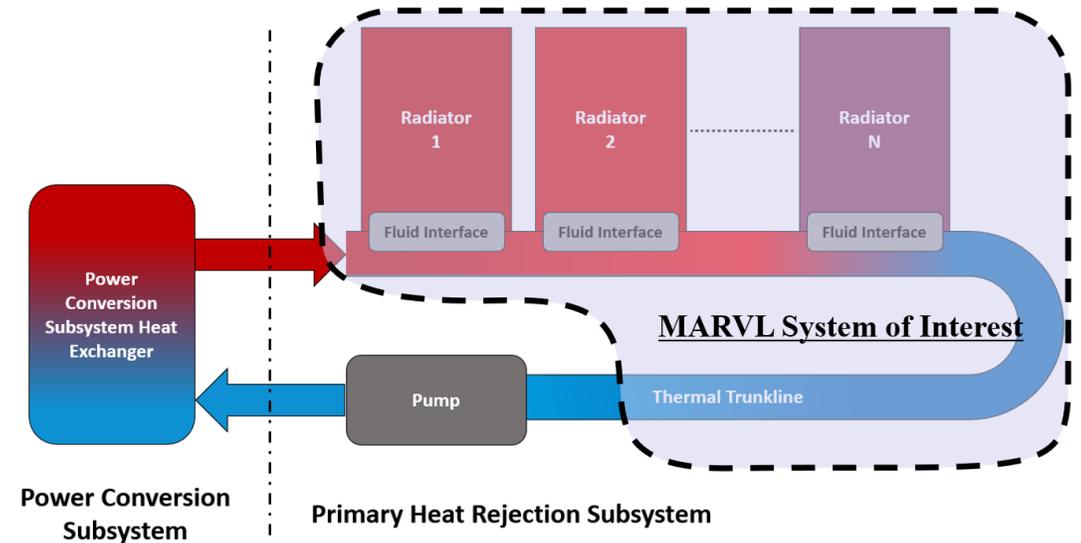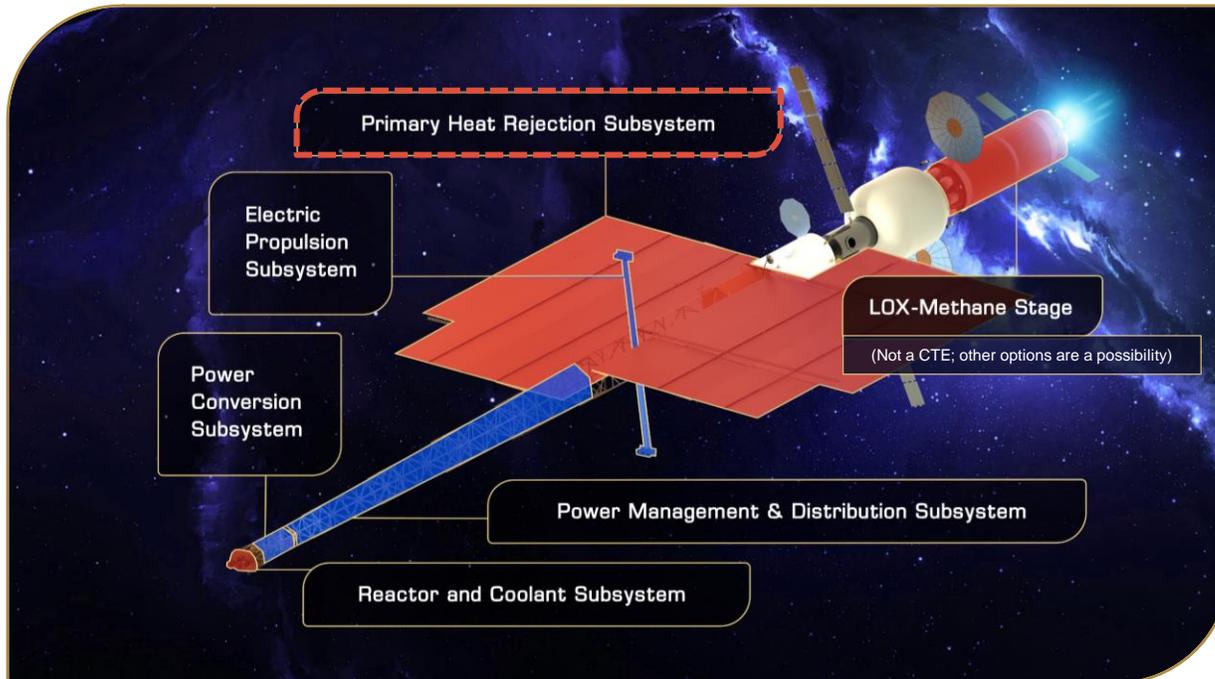
MARVL Project Background

- **Funded through Space Technology Mission Directorate (STMD) Early Career Initiative (ECI) as a two-year project (FY25-26)**
- **Cross-agency team of early career personnel (LaRC, GRC, KSC, MSFC)**

NEP contains five key elements; *The Primary Heat Rejection Subsystem (PHRS) is the largest and most massive element* due to the large amount of reactor waste heat

- $2MW_e$ estimated to produce $4MW_{th}$.
- Surface area **>3,000 m²** and **40-60%** of the total NEP dry mass

- Three key PHRS functions:
  - To (1) accept waste heat, (2) transport waste heat, and (3) radiatively reject waste heat to space
- MARVL System of Interest:
  - Fluid trunkline, fluid interfaces between trunkline and radiators panels, radiator panels

Primary Heat Rejection Subsystem

Electric Propulsion Subsystem

LOX-Methane Stage

(Not a CTE; other options are a possibility)

Power Conversion Subsystem

Power Management & Distribution Subsystem

Reactor and Coolant Subsystem

Five NEP Critical Technology Elements (CTE)

Radiator 1   Radiator 2   Radiator N

Fluid Interface   Fluid Interface   Fluid Interface

Power Conversion Subsystem Heat Exchanger

MARVL System of Interest

Pump

Thermal Trunkline

Power Conversion Subsystem

Primary Heat Rejection Subsystem

Incorporating In-Space Assembly (ISA)

NEP Quad-Wing

NEP Bi-Wing

MARVL

Advantages:

- Compact configuration allows for packaging complete radiator system compacted into one launch vehicle with full deployment

Disadvantages:

- Flight orientation results in view factor losses which increases mass

Advantages:

- ~25% decrease in radiator mass due to reduced area from flying edge onto Sun
- Configuration provides opportunity for ISA applications which reduce cost, schedule, mass, and risk

Disadvantages:

- In-space assembled system cannot be ground tested on Earth

Mission Parameters

- Crewed Mars missions involve many mission phases and locations each with differing environments

- The target application for technology development is a crewed NEP Mars opposition class mission:
  - Crew departure date: 2039
  - Total mission duration: ~3 years
  - Hybrid NEP/chemical vehicle (NEP for cruise phases and chemical stage to enter/exit gravity wells)

- Possible mission locations:
  - Low Earth orbit (LEO), near-rectilinear halo orbit (NRHO), lunar distant high Earth orbit (LDHEO), Mars orbit, Venus flyby, interplanetary space

- Relevant environments:
  - Thermal, vacuum, micrometeoroid and orbital debris (MMOD), radiation, launch loads, in-space loads, microgravity
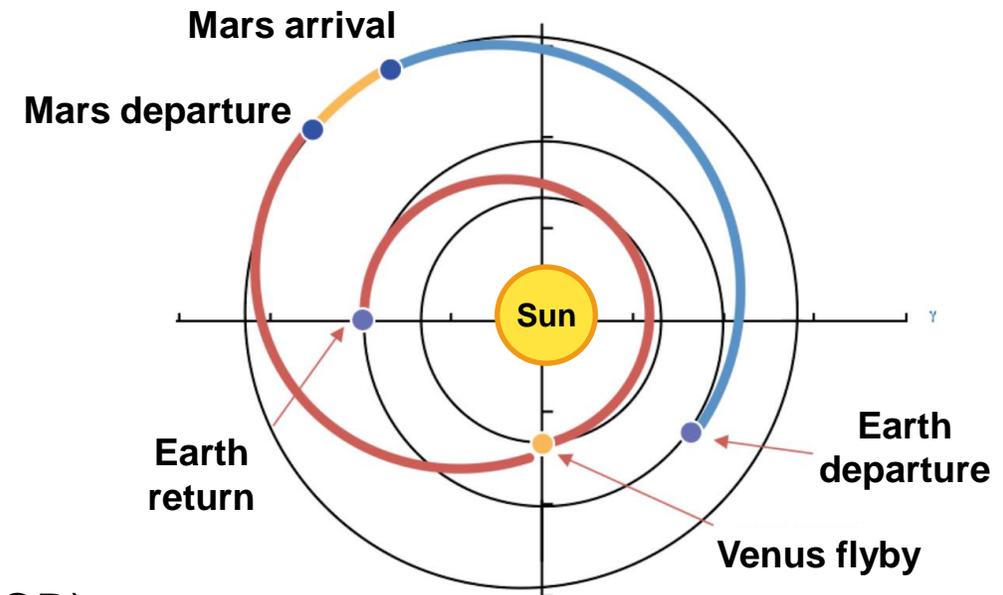
Visualization of the Three Key Thermal Factors

NEP Vehicle

Radiator Panel

Space Thermal Environment

undefined

Fluid Loops

Heat load from reactor

Dependent on
- Mission phase
- Reactor power level

Radiator temperature (T_R)

- Effective temperature: 400 K
- T_R obtained via numerical methods with fluid inlet temperature at 330 K and outlet temperature at 550 K

Environmental sink temperature (T_∞)

Dependent on:
- Optical properties
- Panel's view factor to heat sources
- Temperature of heat sources
- Distance from heat sources

Net thermal power emitted [W]

$$Q = A\varepsilon_{IR}\sigma(T_R^4 - T_\infty^4)$$

$$\%rej = \frac{(T_R^4 - T_\infty^4)}{T_R^4} * 100$$

Heat rejection capability [%]

Maximum $\%rej$ based off $T_\infty = 0$ assumption

Chart legend: TSINK, Tr (average), %rej (constant Tr). Y-axis left: Heat Rejection Capability (%), Y-axis right: Temperature (K), X-axis: Time

6
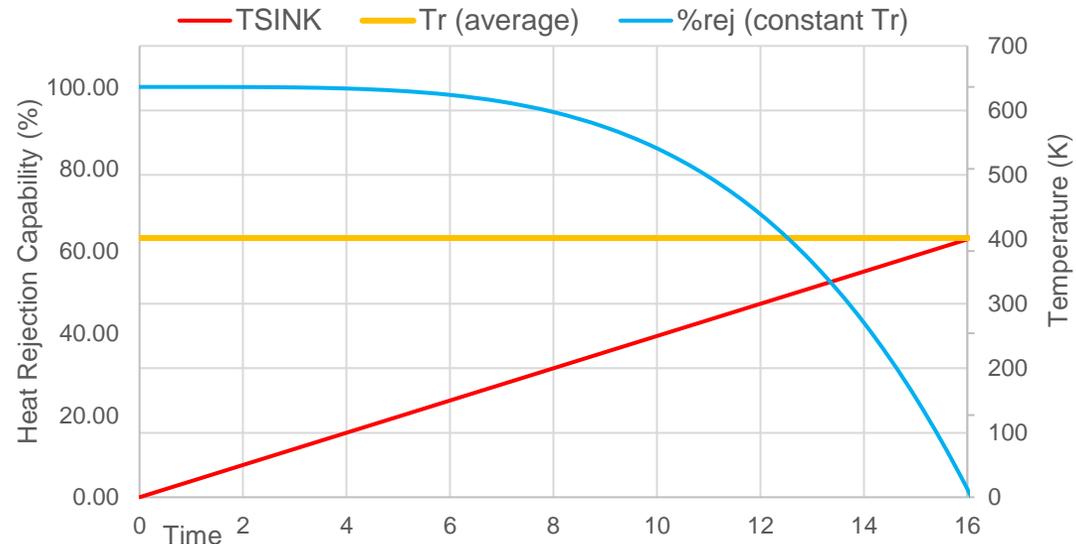
Three sources of environmental heating:

- Solar radiation
  - **Direct solar**
  - **Albedo** (solar radiation reflected by nearby planets)
- Infrared (IR) radiation
  - **Outgoing longwave radiation (OLR)** (emitted by nearby planets)

F_{IR} = absorbed incident IR from OLR

F_S = absorbed direct solar + absorbed albedo

$F_{IR} + F_S = F_A$ = total absorbed flux

$$T_\infty = \left(\frac{F_A}{\sigma \varepsilon_{IR}} \right)^{\frac{1}{4}}$$

Legend

←	Direct Solar
←---	Reflected Solar
~←	Emitted IR
--←	Reflected IR
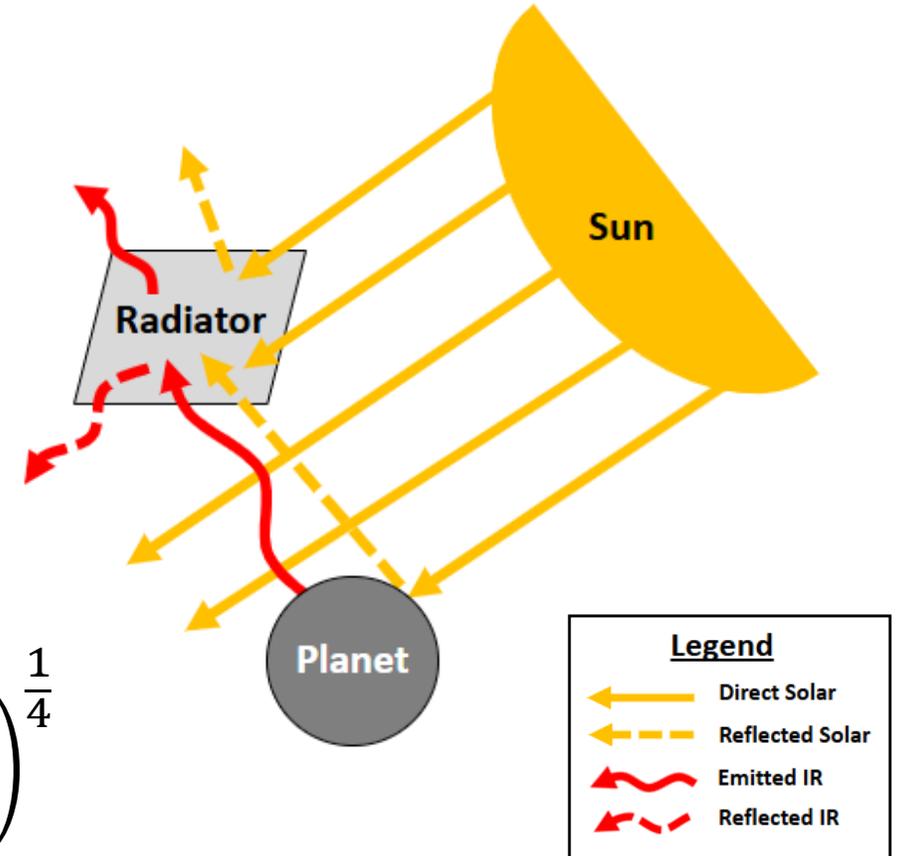
Alter view factor of the panel to environmental heating sources to affect environmental sink temperatures. **Which panel orientations are ideal?**

Study Objectives and Steps

1. **Envelope a wide variety of mission phases to define the worst case hot and cold environments**

2. **Understand effect of panel orientation on environmental sink temperature and heat load capacity**

3. **Select ideal panel orientations to align with radiator temperature and heat load capacity constraints**

4. **Identify absolute extrema of environmental heat sink temperatures across the whole mission**

Phase 1: Foundations		Phase 2: Research	Phase 3: Analysis	
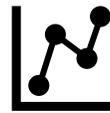
- Defined the environmental heating sources
- Enveloped hot and cold cases for a wide variety of space environments

- Created ANSYS Thermal Desktop model to run orbital cases and apply defined heating source values

- Ran Thermal Desktop model and record findings

- Selected panel orientations that align with mission objectives (for ideal heat load capacity)

- Identified the absolute extrema of environmental sink temperatures
- Identified other significant characteristics of the data

Environments Enveloped by Extreme Hot and Cold Cases

LEO, NRHO, LDHEO, Mars orbits, Venus flyby, and interplanetary space

Direct solar	Albedo	OLR	**+**	Additional considerations:

Additional considerations:
- LEO: albedo correction factors
- Eclipse cases

Case	Direct solar (W/m²)	Albedo	OLR (W/m²)
Hot Case	1414	0.3	332
Cold Case	1322	0.4	150

LEO Extreme-Case Thermal Environments Table
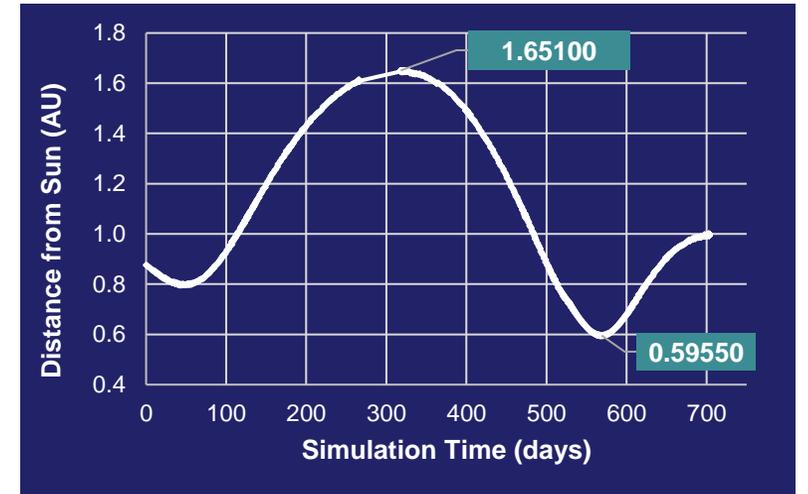
Spacecraft distance from the Sun for trajectory profile of sample Mars mission

$$Interplanetary\ solar\ flux = \frac{1}{d^2} \times 1367\ W/m^2$$

Incident IR flux (Q_{IR}) and incident solar flux (Q_s) values calculated through Thermal Desktop

Optical Properties:
ε = 1
α = 1
to capture total incident flux
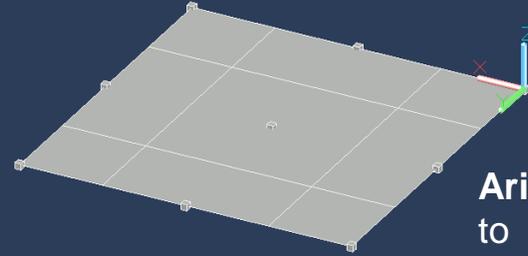
Dimensions:
1 m x 1 m; 0 thickness

Arithmetic nodes set in order to record instantaneous values
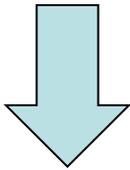
Optical properties are substituted into the equation:

$$F_A = (\alpha_s * Q_s) + (\varepsilon_{IR} * Q_{IR})$$

in Microsoft Excel to calculate total absorbed flux (F_A) used in the following equations
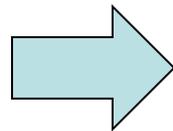
Environmental sink temperature

$$T_\infty = \left(\frac{F_A}{\sigma \varepsilon_{IR}}\right)^{\frac{1}{4}}$$

Heat rejection capability (%)

$$\%rej = \frac{(T_R^4 - T_\infty^4)}{T_R^4} * 100$$

Radiator temperatures and **optical properties** are defined in Excel and can be changed parametrically
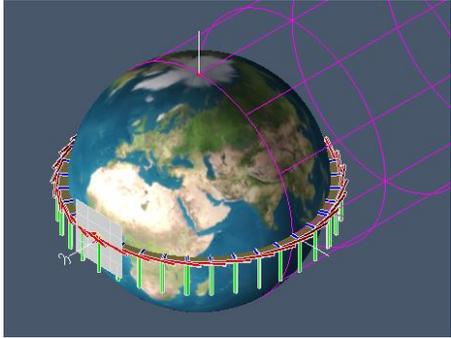
500 km altitude

1100 km altitude
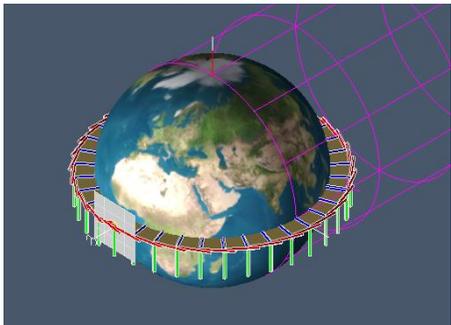
LEO

9:2 lunar synodic-resonant, southern L2 Lagrangian point
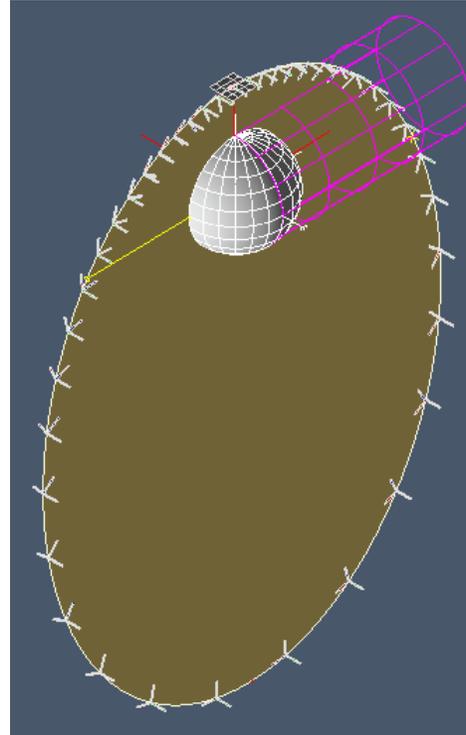
NRHO

250x7660km
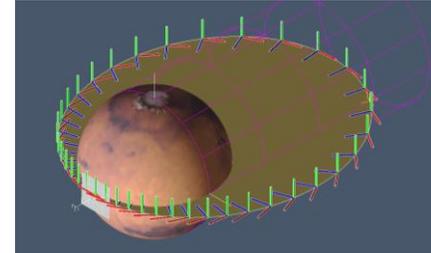
1-Sol orbit
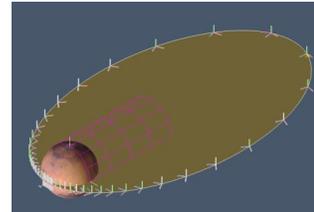
2-Sol orbit
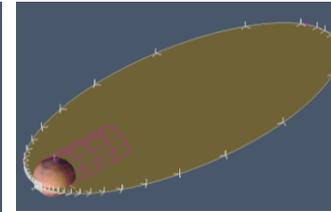
5-Sol orbit
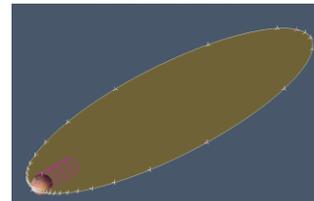
10-Sol orbit
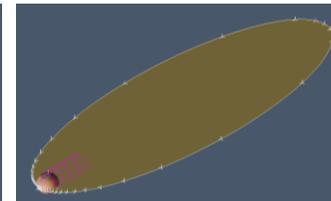
Mars orbits

Sample Venus flyby trajectory

Vector to Venus

Vector to Sun
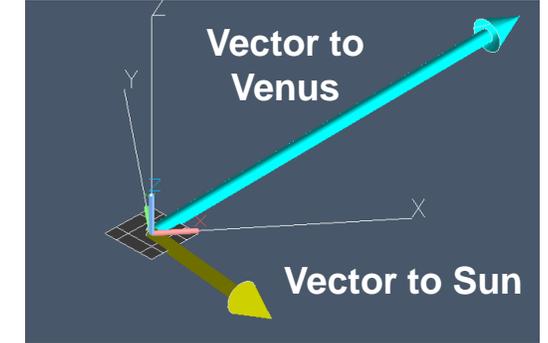
Venus flyby closest pass model
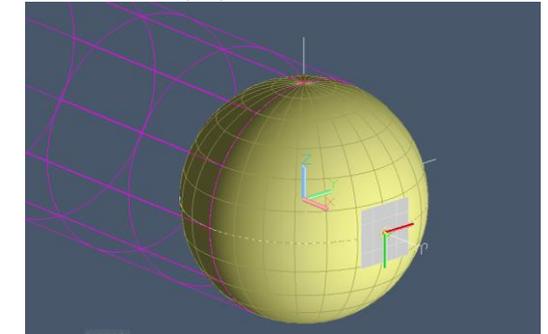
Venus flyby

Model Considers the Wide Variety of Environments

- Orbits must be defined to accurately represent envelope of possible variations in trajectory and orbital parameters

- Considered in the model are the environmental heating sources for extreme case hot and cold case data

Beta Angle Sweep
Range of possibilities measured to account for mission design changes (orbit inclination angles) and natural variations due to right ascension of the ascending node (RAAN) shifts due to planetary rotation

45°   0°
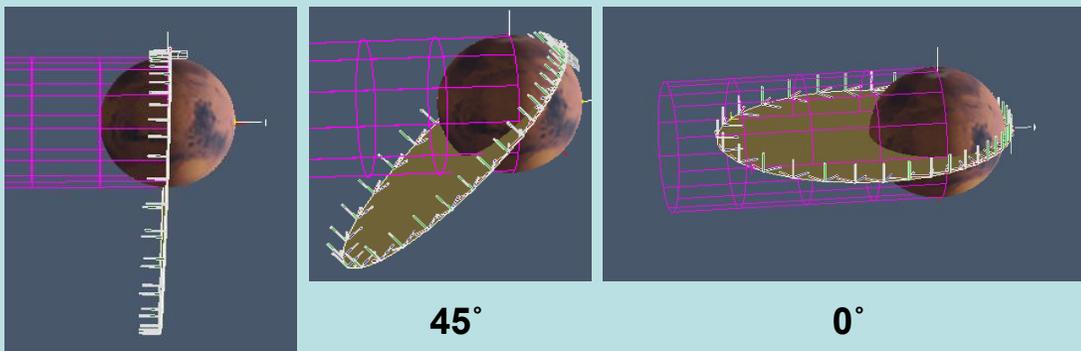
90°   **Beta angle variations for <1-Sol Mars orbit**

Eclipses
Position intervals adjusted for more eccentric orbits to include shadow entry and exit

Shadow entry

Positions measured within shadow

Shadow exit
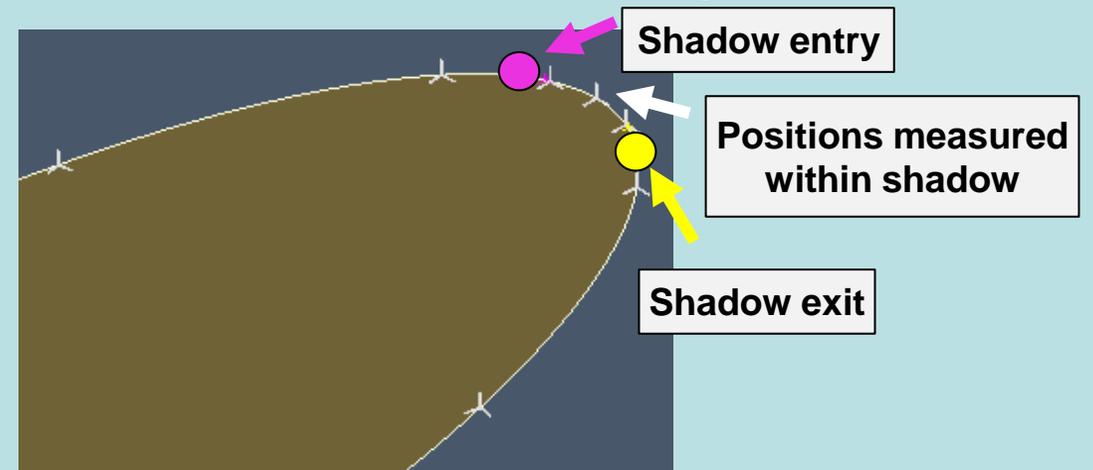
0° beta angle Mars 5-Sol orbit, around apoapsis

Some unknowns had to be sorted out to properly outline the envelope of possible Mars orbit cases

Orbit modeled in Thermal Desktop:
Mars 1-Sol orbit, 0˚ beta angle

Periapsis
on Sun side
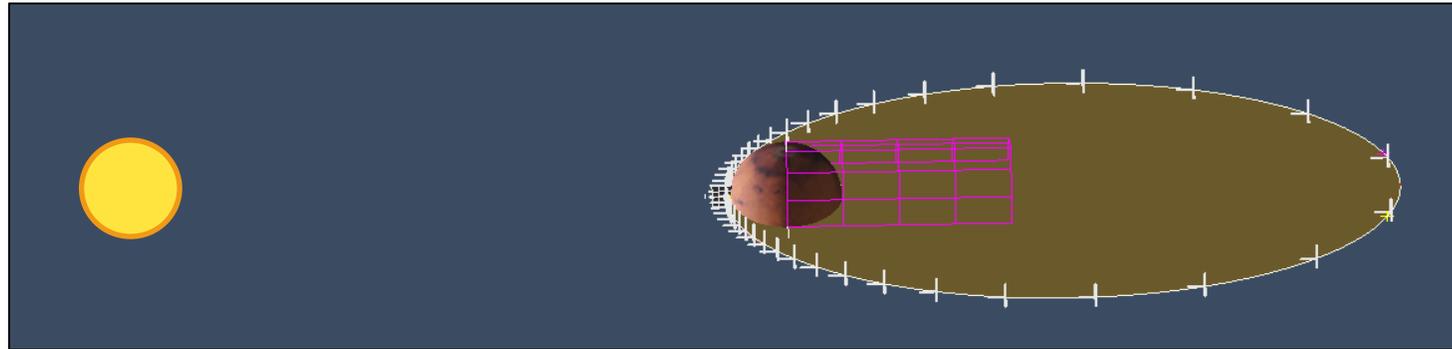
Apoapsis
on Sun side
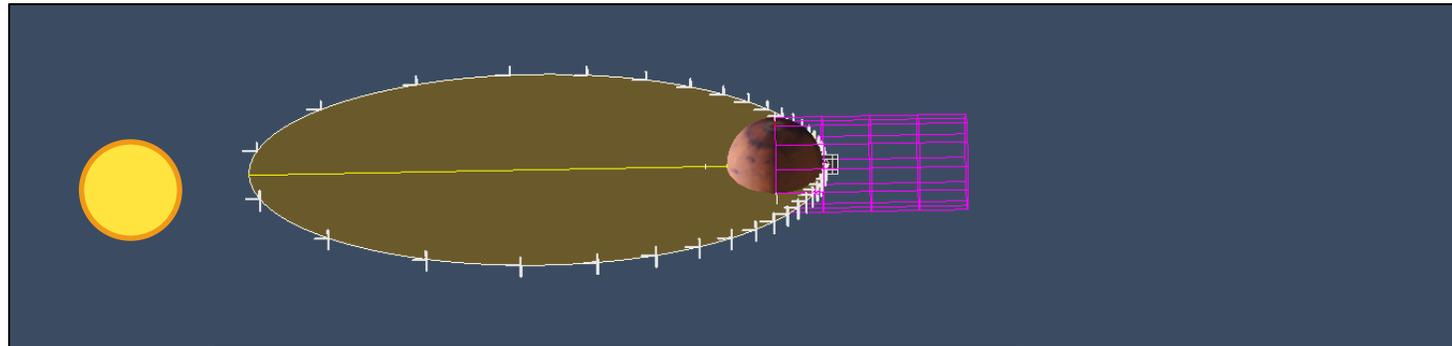
Modeling Mars: Apoapsis Position Relative to the Sun

Some unknowns had to be sorted out to properly outline the envelope of possible Mars orbit cases

Orbit modeled in Thermal Desktop:
Mars 1-Sol orbit, 0˚ beta angle
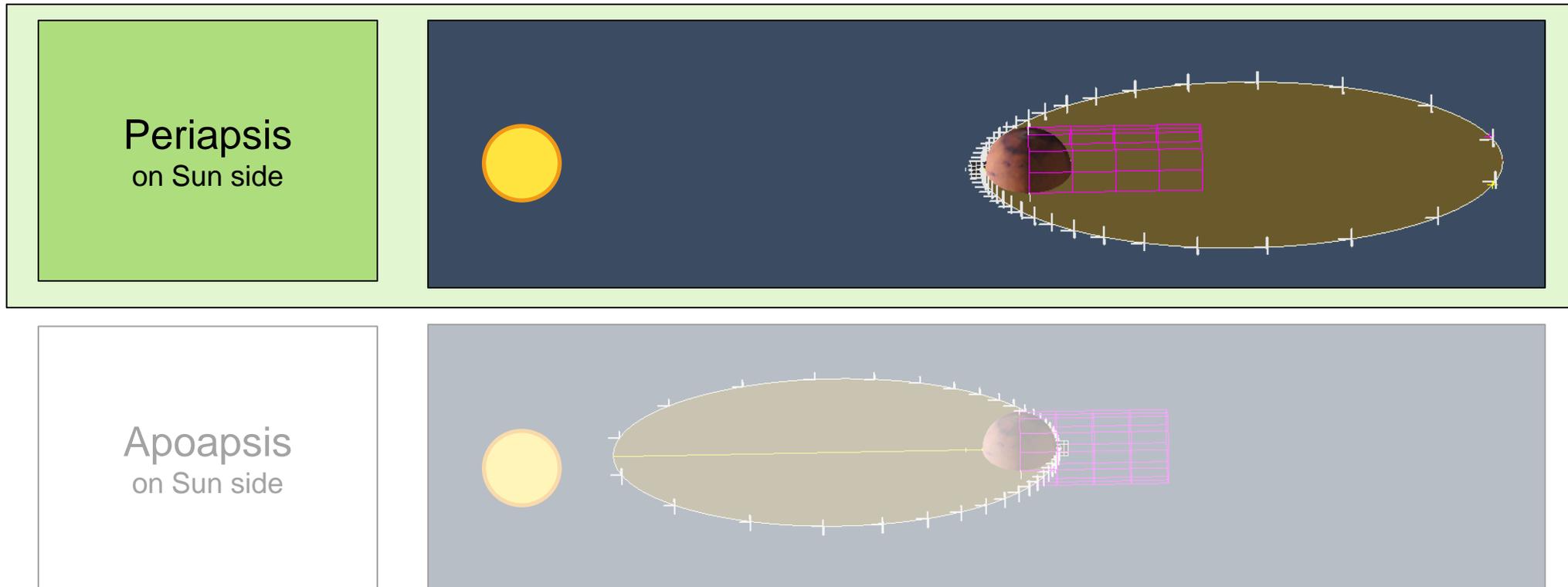
To reach absolute max and min environmental sink temperatures, model periapsis on Sun side

Study Compares Six Panel Orientations

Velocity vector (VV) points along orbital path

01 – Face to Planet (Edge to VV)

02 – Edge to Planet (Edge to VV)

03 - Edge to Planet (Face to VV)

04 – Face to Sun

05 – Edge to Sun (Horizontal)

06 - Edge to Sun (Vertical)

Panel orientations displayed on LEO at 1100 km

LEO (2) (altitude variations)
NRHO (1)
Mars (5) (eccentricity variations)
Venus close approach (1)

= 9 locations → **x 6 orientations** → **x 3 beta angles**

↓

x 2 cases (hot/cold)

Venus flyby trajectory = 1 location → **x 2 orientations**
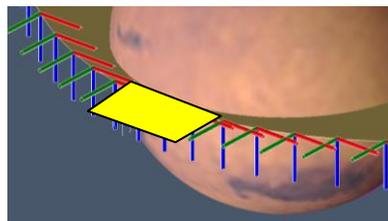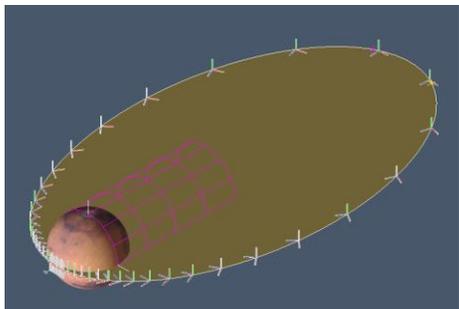
Total cases
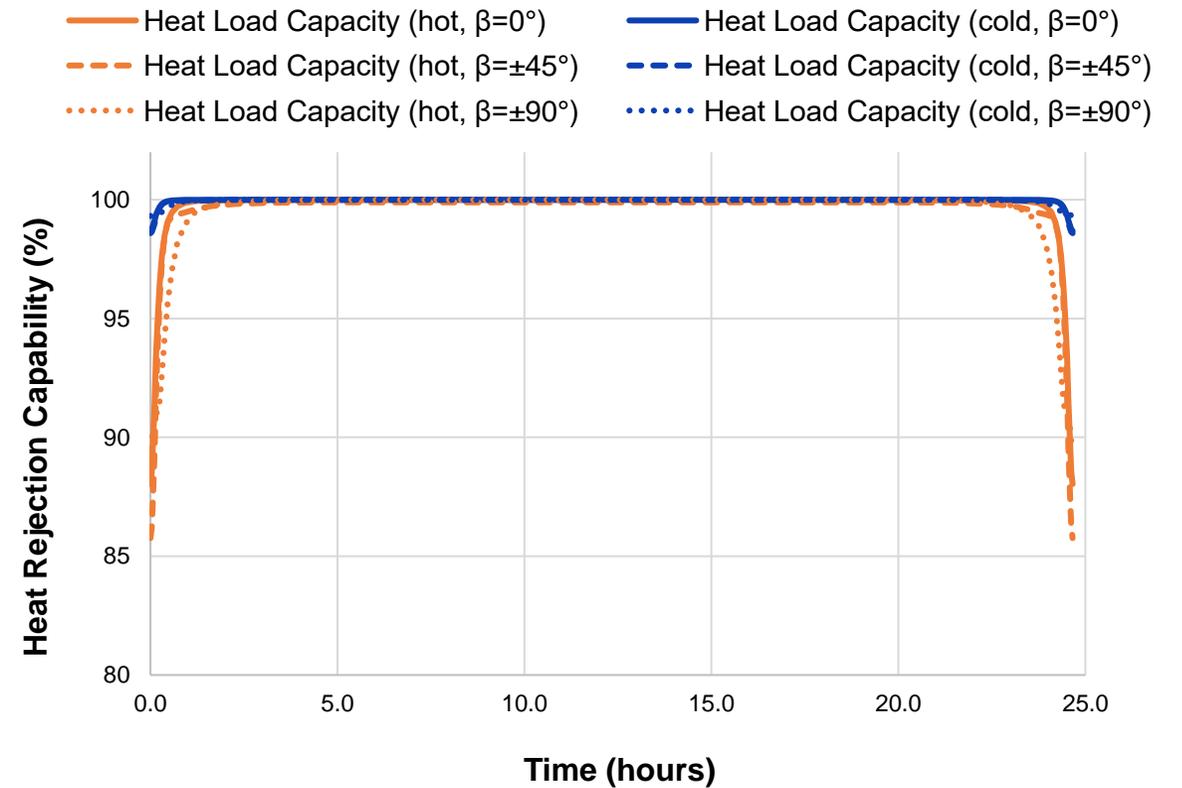modeled in study:
328

Modeled: 1-Sol Martian Orbit

Edge to Sun (Horizontal)

Edge to Sun (Horizontal)
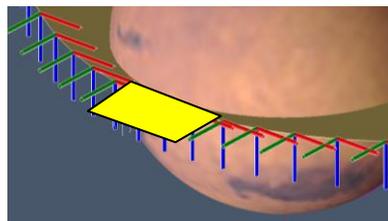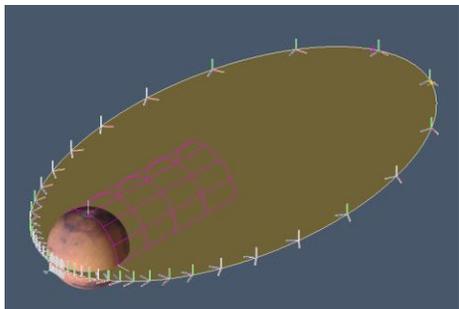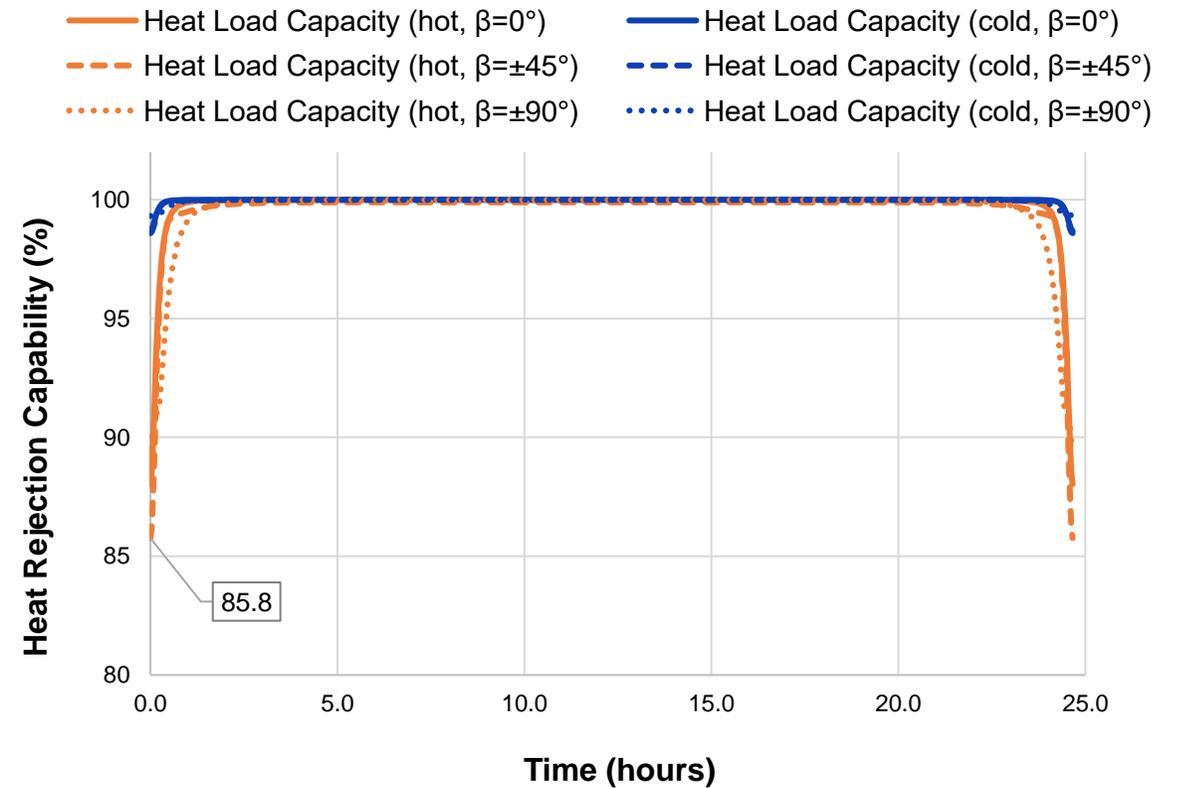
Each curve is calculated with instantaneous incident flux values, for specified positions throughout the orbit
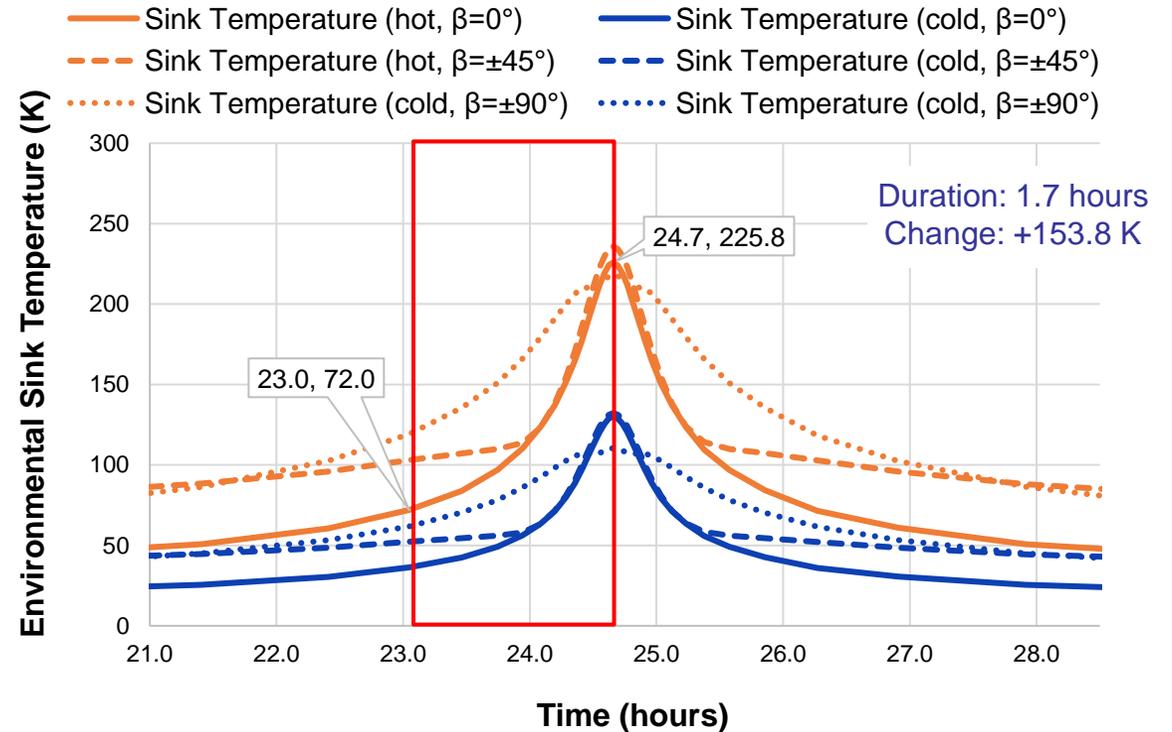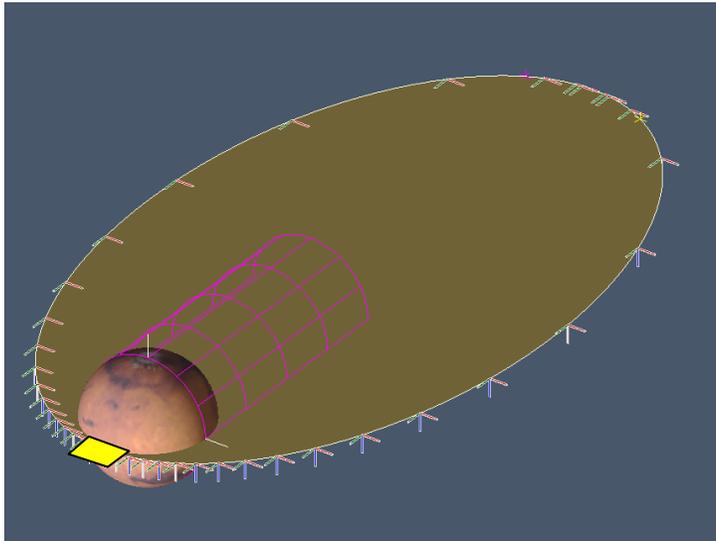
Data Collection and Interpretation

Modeled: 1-Sol Martian Orbit

Each curve is calculated with instantaneous incident flux values, for specified positions throughout the orbit

Large Temperature Gradients

Modeled: 1-Sol Martian Orbit

Edge to Sun (Horizontal)

Legend:
- Sink Temperature (hot, β=0°)
- Sink Temperature (hot, β=±45°)
- Sink Temperature (cold, β=±90°)
- Sink Temperature (cold, β=0°)
- Sink Temperature (cold, β=±45°)
- Sink Temperature (cold, β=±90°)

Y-axis: Environmental Sink Temperature (K)
X-axis: Time (hours)

Annotations:
- 24.7, 225.8
- 23.0, 72.0
- Duration: 1.7 hours
- Change: +153.8 K

Large temperature gradients are a consideration for sensitive equipment or components with low thermal time constants (Radiator: 10s of seconds to a minute)
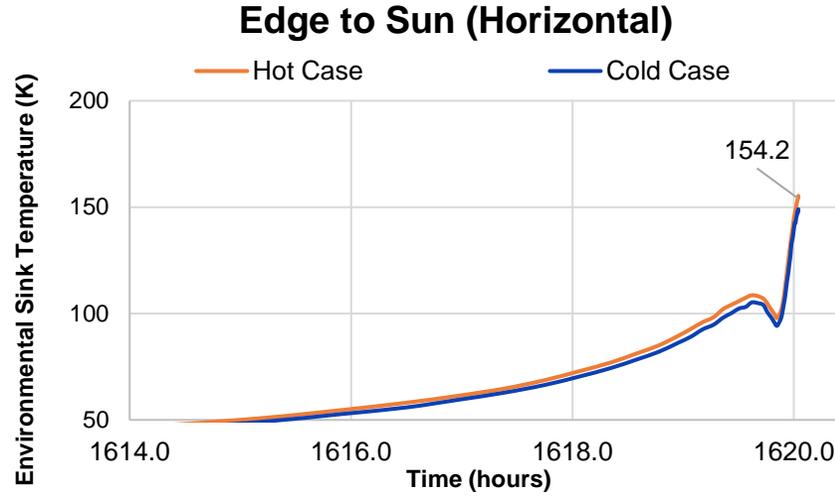
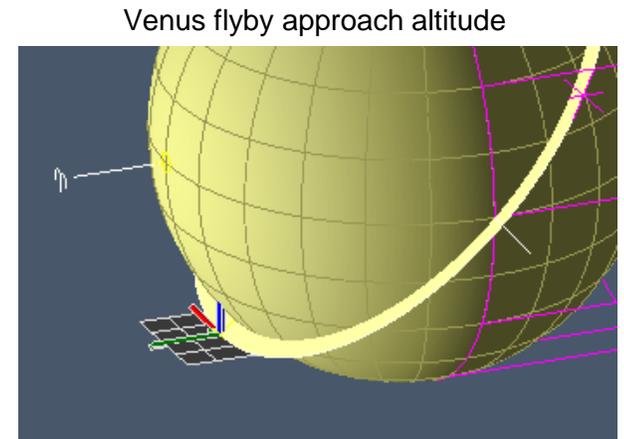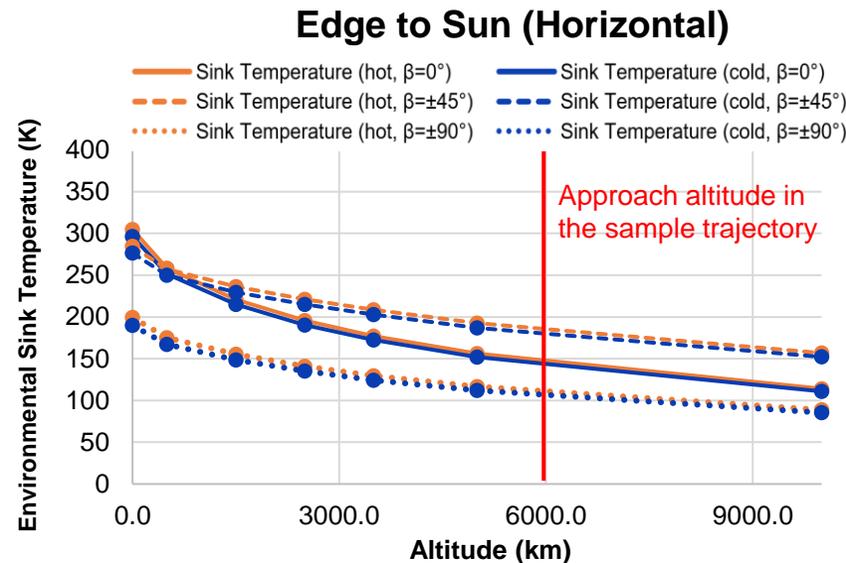# Venus Flyby is Modeled with Two Methods

Sample Flyby Trajectory

- Provided by Systems Analysis and Concepts Directorate (SACD) at LaRC
- Closest approach is 6000 km
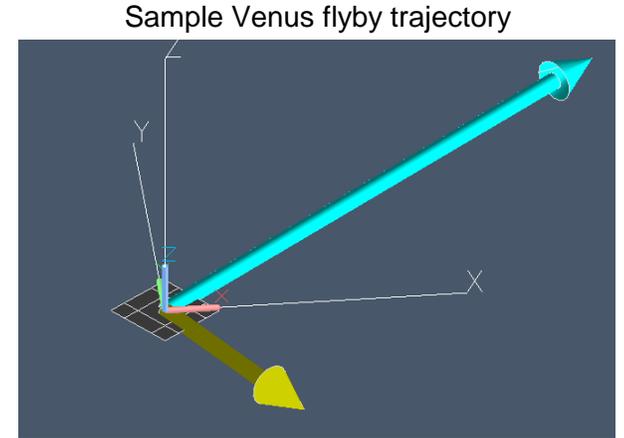
Approach Altitude Method

- Approach measures various altitudes as possible closest approaches to Venus
- Method gathers information on flux values of various positions, without requiring the flyby trajectory

Edge to Sun (Horizontal)

Hot Case — Cold Case

154.2

Environmental Sink Temperature (K) vs Time (hours)

Edge to Sun (Horizontal)

Sink Temperature (hot, β=0°) — Sink Temperature (cold, β=0°)
Sink Temperature (hot, β=±45°) — Sink Temperature (cold, β=±45°)
Sink Temperature (hot, β=±90°) — Sink Temperature (cold, β=±90°)

Approach altitude in the sample trajectory

Environmental Sink Temperature (K) vs Altitude (km)

Sample Venus flyby trajectory

Venus flyby approach altitude
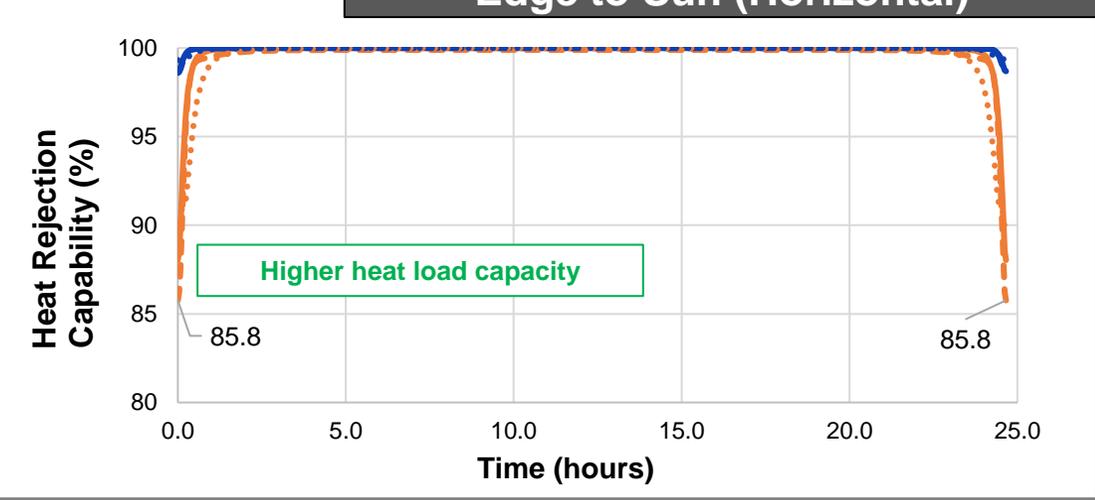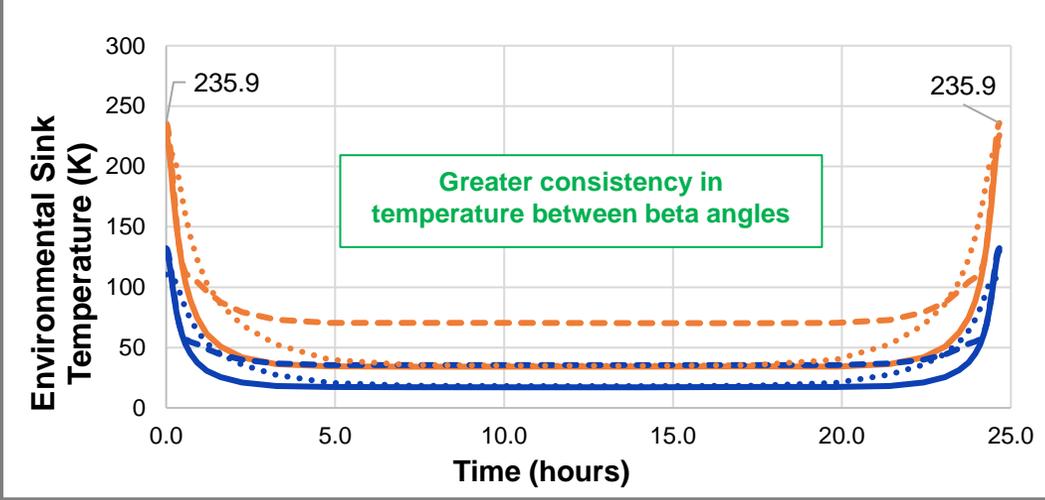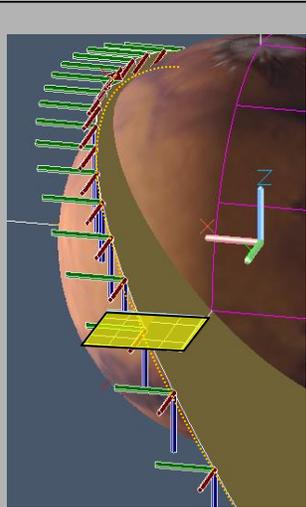
Changing Optical Properties and Radiator Temperature
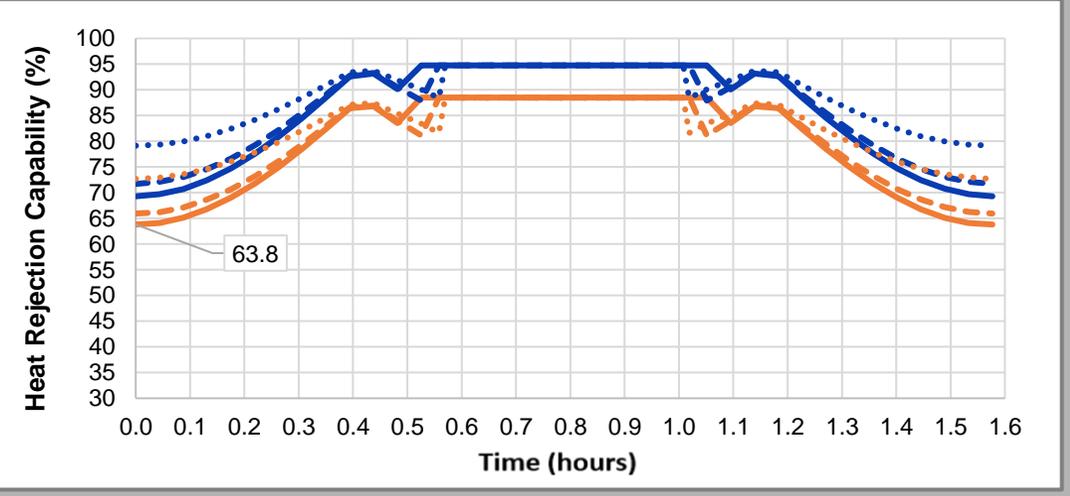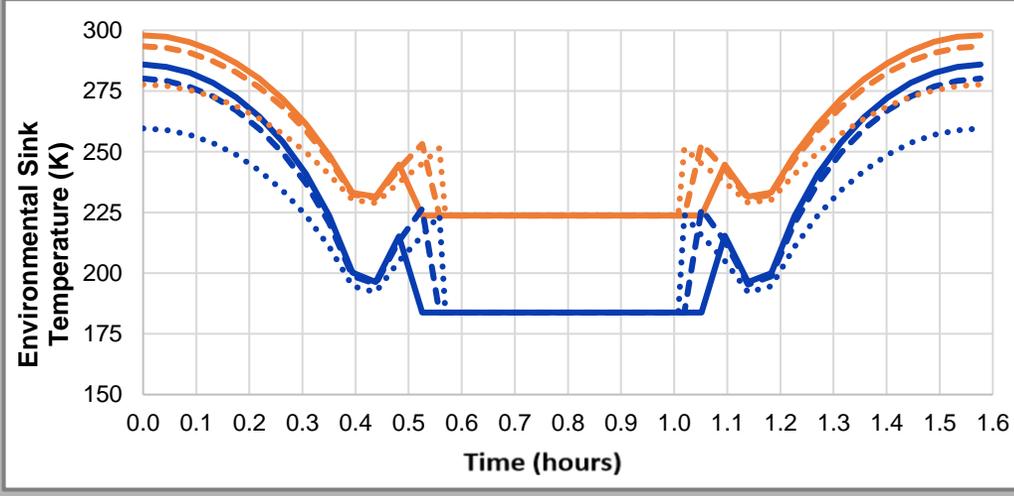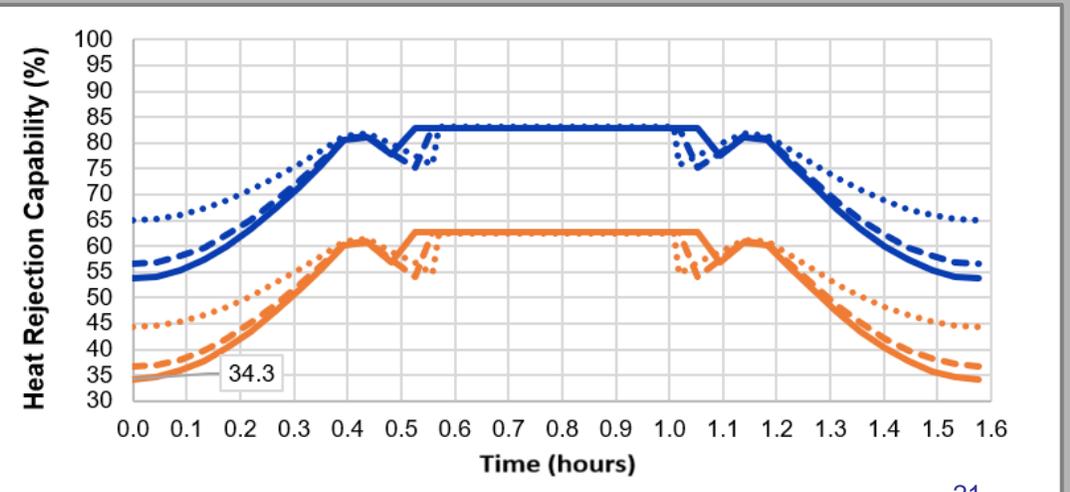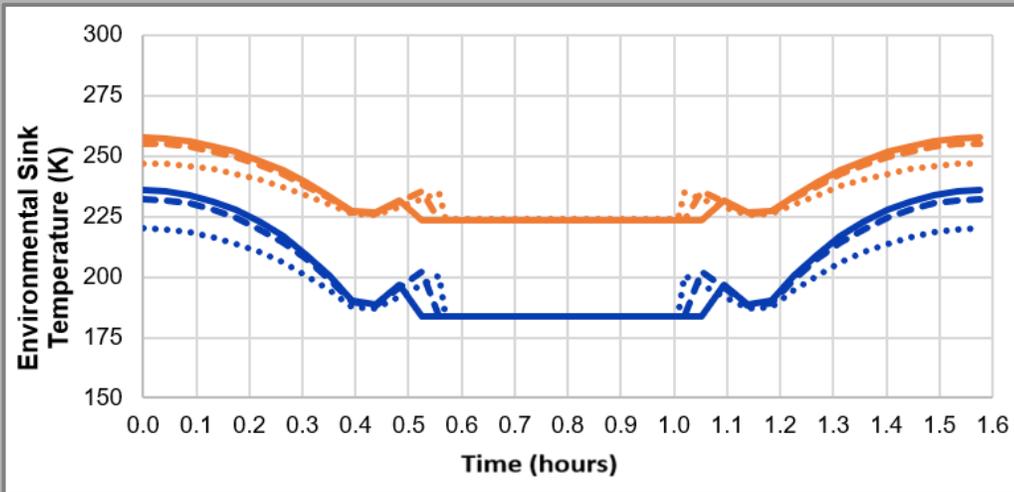
Select Orientations and Beta Angles to Reduce Cases

1-Sol Mars orbit

Legend:
- (hot, β=0°) — solid orange
- (hot, β=±45°) — dashed orange
- (hot, β=±90°) — dotted orange
- (cold, β=0°) — solid blue
- (cold, β=±45°) — dashed blue
- (cold, β=±90°) — dotted blue

Edge to Sun (Horizontal)

Environmental Sink Temperature (K) vs Time (hours): 235.9 ... 235.9

Greater consistency in temperature between beta angles

Heat Rejection Capability (%) vs Time (hours): 85.8 ... 85.8

Higher heat load capacity

Edge to Mars (Edge to VV)

Environmental Sink Temperature (K) vs Time (hours): 259.2 ... 259.2

Higher temperature fluctuations between beta angles

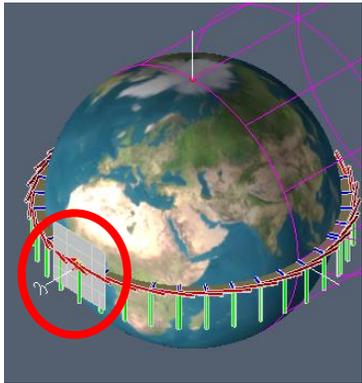Heat Rejection Capability (%) vs Time (hours): 80.7 ... 80.7

Lower heat load capacity

Environmental Sink Temperature Extrema are Identified

Location and panel orientation combinations: 328 — reduced to → 41
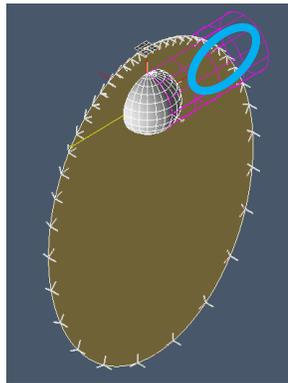
Reactor powered **off**

Maximum: 298 K

LEO, 500 km altitude
0˚ beta angle

Face to Earth (Edge to VV)
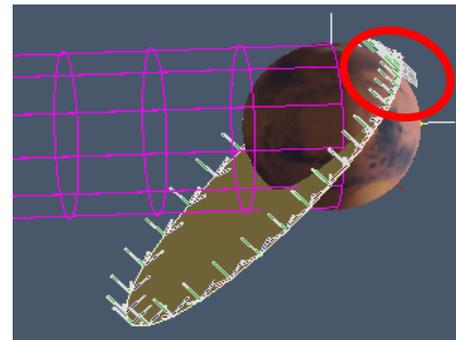Position: subsolar point

Minimum: 30 K

NRHO
0˚ beta angle

Face to Sun
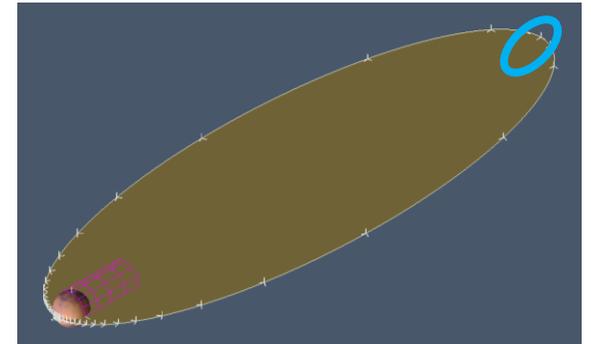Position: within shadow

Reactor powered **on**

Maximum: 236 K

Mars orbit, <1-sol
45˚ beta angle

Edge to Sun (Horizontal)
Position: periapsis

Minimum: 5 K

Mars orbit, 10-sol
0˚ beta angle

Edge to Sun (Horizontal)
Position: apoapsis

Study Objectives Complete

1. Identify the hot and cold case extrema among a wide variety of mission environments ✓

2. Analyze the effect of panel orientation on environmental sink temperature and heat load capacity ✓

3. Select ideal panel orientations to align with radiator temperature and heat load capacity constraints ✓

4. Identify absolute extrema of environmental heat sink temperatures across the whole mission ✓

Future Work Leveraging Study Results

Since completed:

Now may:

1.

| Identify the hot and cold case extrema among a wide variety of mission environments | → | Apply collected information for future LDHEO study |

2.

| Analyze the effect of panel orientation on environmental sink temperature and heat load capacity | → | Inform trade between commissioning orbits |

3.

| Select ideal panel orientations to align with radiator temperature and heat load capacity constraints | → | Implement Thermal Desktop model for full vehicle thermal studies |

4.

| Identify absolute extrema of environmental heat sink temperatures across the whole mission | → | Use environmental sink temperature curves to predict component transient performance |

Concluding Remarks

Accomplished within the study:

- Identified the hot and cold case extrema among a wide variety of mission environments
- Analyzed the effect of panel orientation on radiator temperature and heat load capacity
- Selected ideal panel orientations to align with radiator temperature and heat load capacity constraints
- Identified absolute extrema of environmental heat sink temperatures across the whole mission

Benefits for future studies:

- The model generated in this study uses a representative 1x1 panel to measure thermal environment with parameterized optical properties and radiator temperature
- The model may serve as useful tools for future crewed space missions, missions involving radiators or temperature sensitive equipment, or missions requiring analysis of thermal environments

Questions?

Backups

Panel Orientation Selections

Orbit	Specification	Orientation	Case	Beta Angle
LEO	500 km	Face to Earth (Edge to VV)	Hot	0
			Cold	52
		Face to Sun	Hot	0
			Cold	52
		Edge to Sun (Horizontal)	Hot	52
			Cold	0
	1100 km	Face to Earth (Edge to VV)	Hot	0
			Hot	52
			Cold	25
			Cold	52
		Face to Sun	Hot	0
			Hot	52
			Cold	25
			Cold	52
		Edge to Sun (Horizontal)	Hot	52
			Cold	0
NRHO	9:2 lunar synodic-resonant, southern L2 Lagrangian point	Face to Sun	Hot	0
			Hot	45
			Cold	0
			Cold	45
		Edge to Sun (Vertical)	Hot	0
			Hot	90
			Cold	0
			Cold	45

| Orbit	Specification	Orientation	Case	Beta Angle
Martian Orbits	<1-Sol	Edge to Sun (Vertical)	Hot	0
			Cold	0
	1-Sol	Edge to Sun (Horizontal)	Hot	0
			Hot	90
			Cold	0
	2-Sol	Edge to Sun (Horizontal)	Hot	0
			Hot	90
			Cold	0
	5-Sol	Edge to Sun (Horizontal)	Hot	0
			Hot	90
			Cold	0
	10-Sol	Edge to Sun (Horizontal)	Hot	0
			Hot	90
			Cold	0
Venus Flyby	Sample trajectory	Edge to Sun (Horizontal)	Hot	0
			Hot	45
			Cold	90

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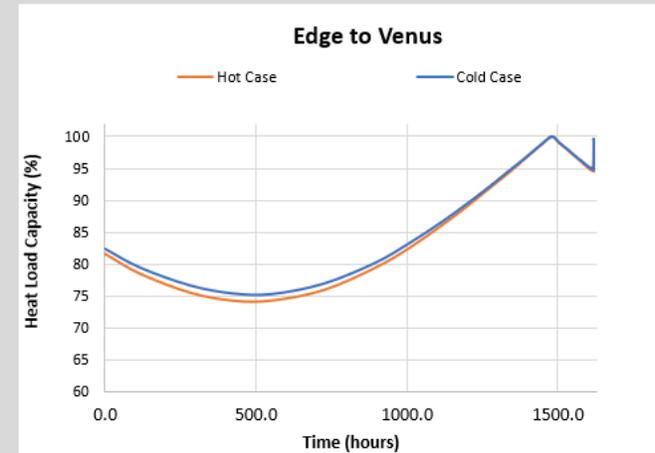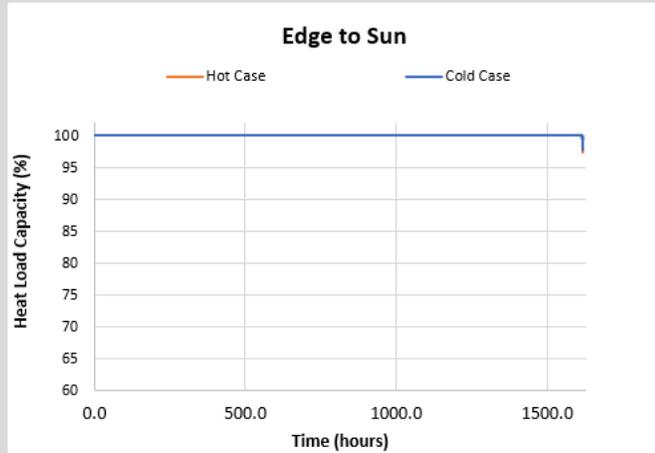
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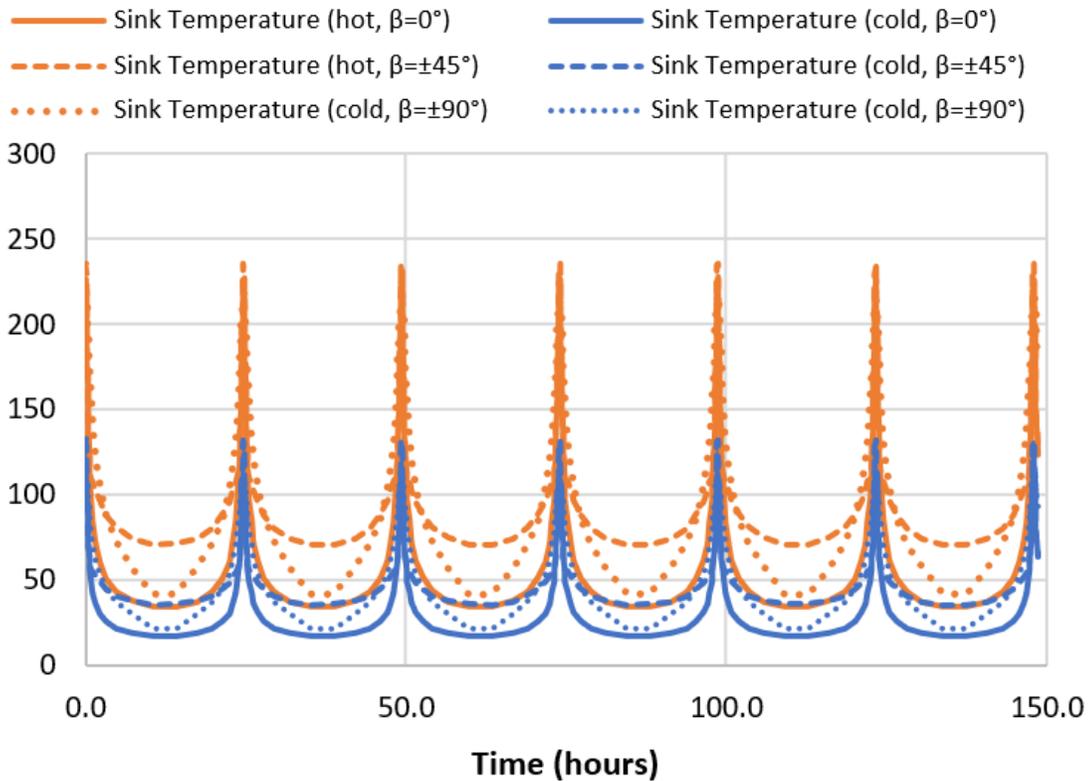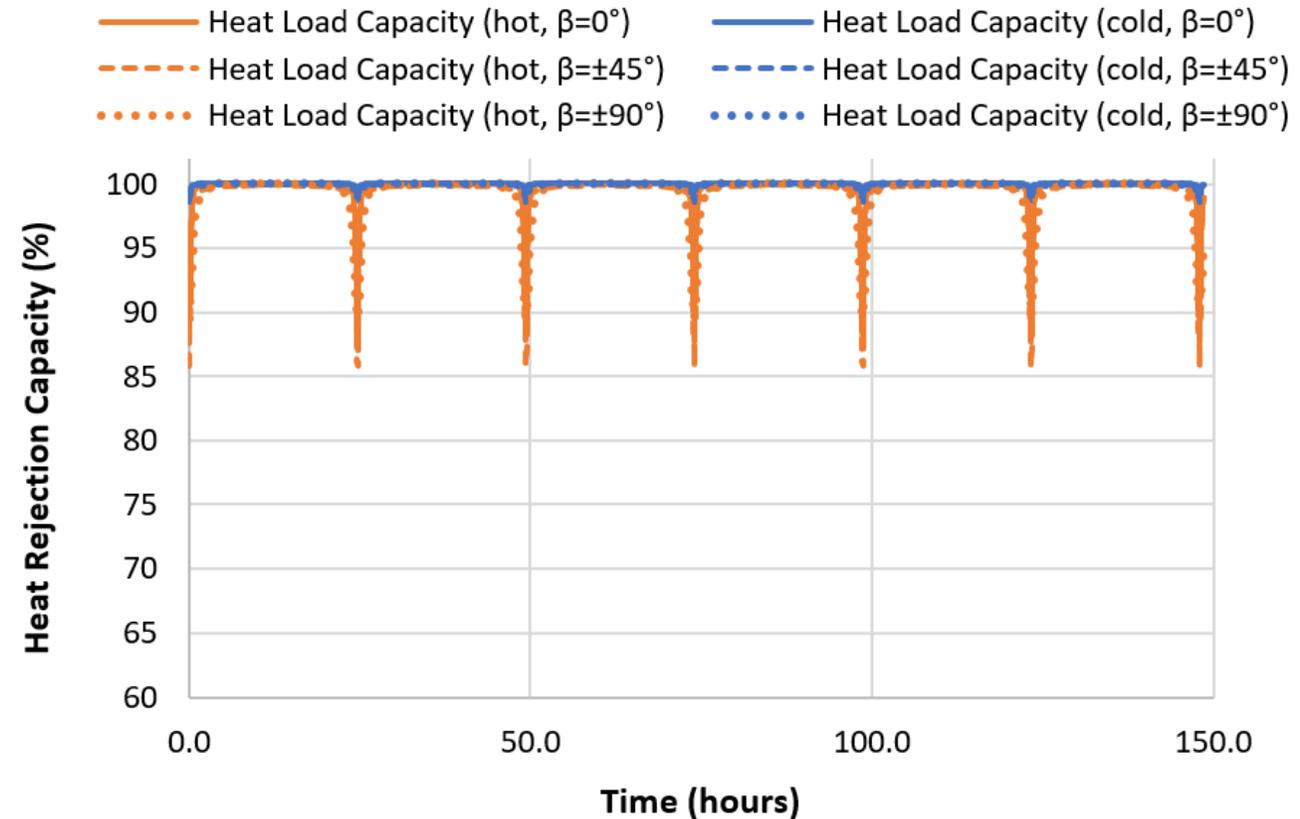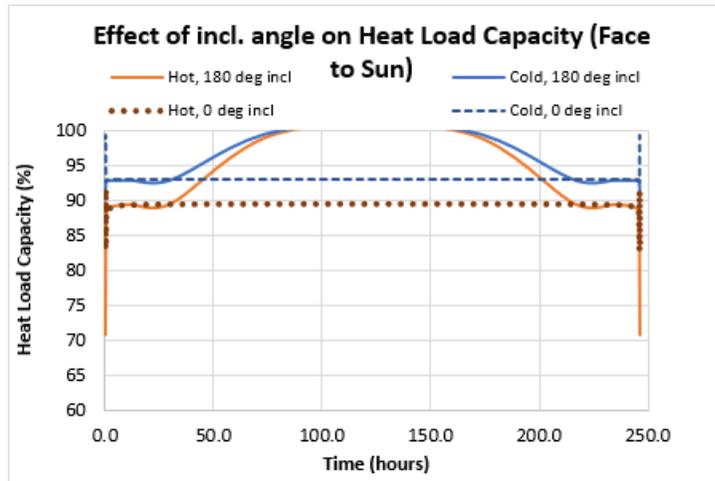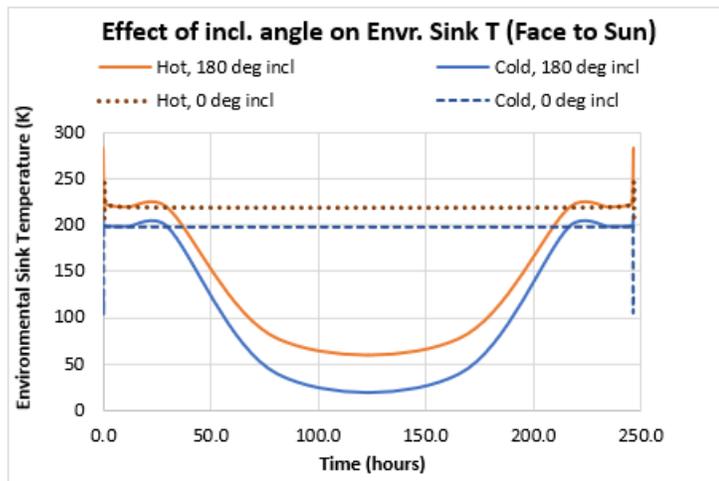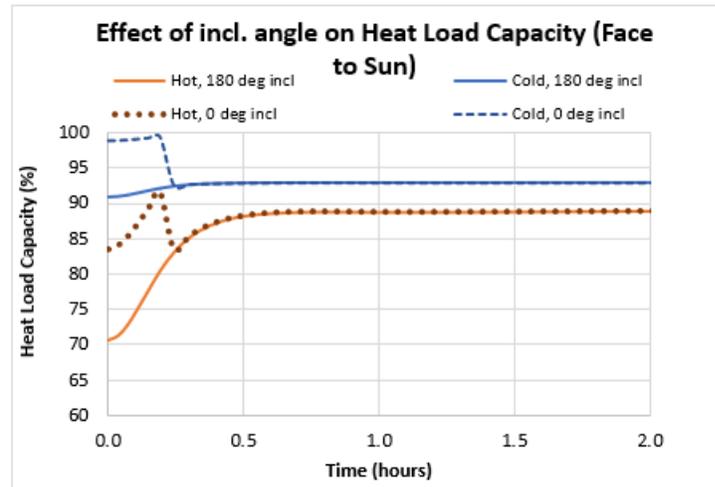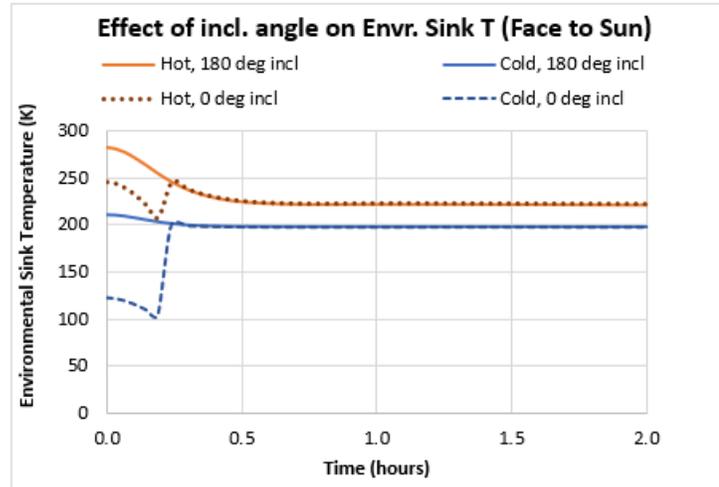
180-degree inclination angle represents periapsis on sun-side.
0-degree inclination represents apoapsis on sun-side.

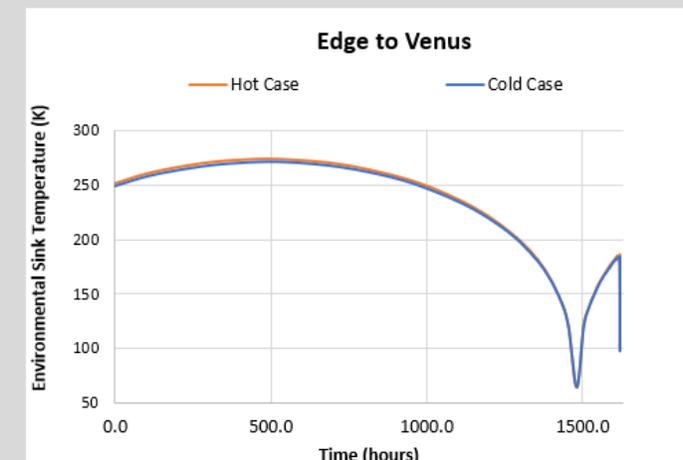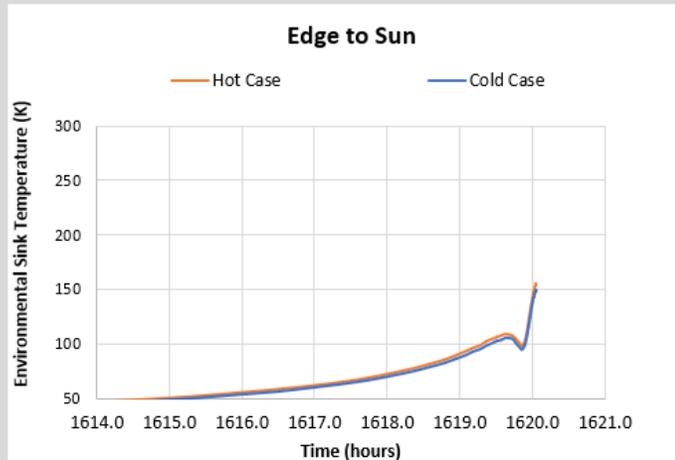# Results of Venus Flyby Sample Trajectory

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