Modular Assembled Radiators for NEP VehicLes (MARVL)

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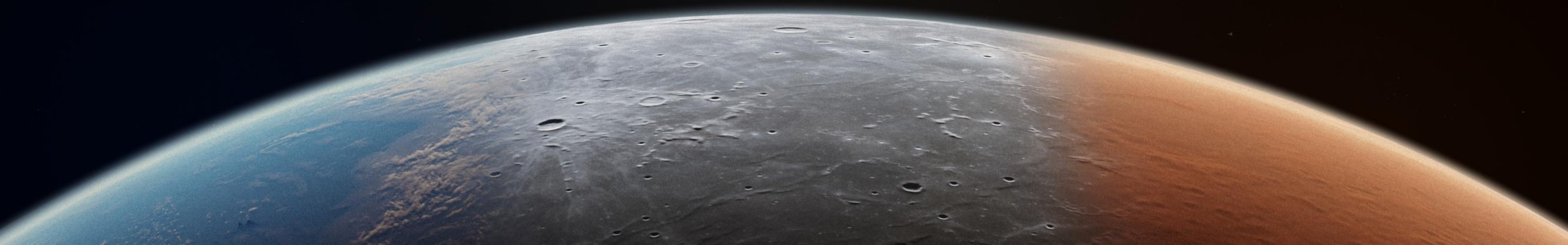

Team Members

Team Management
- **Amanda Stark (LaRC-D206), PI/PM**
- **Will Grier (LaRC-D206), SE&I Lead**
- Felicia Webster (LaRC-B602D), RA

Radiator Design
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Fluid Loop Design
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Mechanical and Structural Design
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Systems Analysis
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- Diego Perea (OSTEM)
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Mentors
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- Shawn Britton, PM Mentor
- Terry Nienaber, SE&I Mentor
- Jim Sanzi (GRC), Radiator Design
- Melissa Hill, Mod-Sim
- Jimmy Ecker, Autonomy/Robotics
- Chetan Patel (JSC), Mod-Sim
- Laura Lucier (JSC), Large Scale iSA

Other Team Members
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- Andrew McMahon, Systems Engineering (LaRC-D208)
- Hector Gortaire, Safety, Mission Assurance (LaRC-C202)
- Emanual Grella, Redundancy Study (AMA)
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- Justin Westmoreland, Trick Engineer for Mod/Sim (JSC-ER711)
- Thomas Brain, Trick Engineer for Mod/Sim (JSC-ER711)
- Christopher Sullivan, Trick Engineer for Mod/Sim (JSC-ER711)
- Cory Foreman, Trick Engineer for Mod/Sim (JSC-ER711)

Names in bold denote the original proposal team.

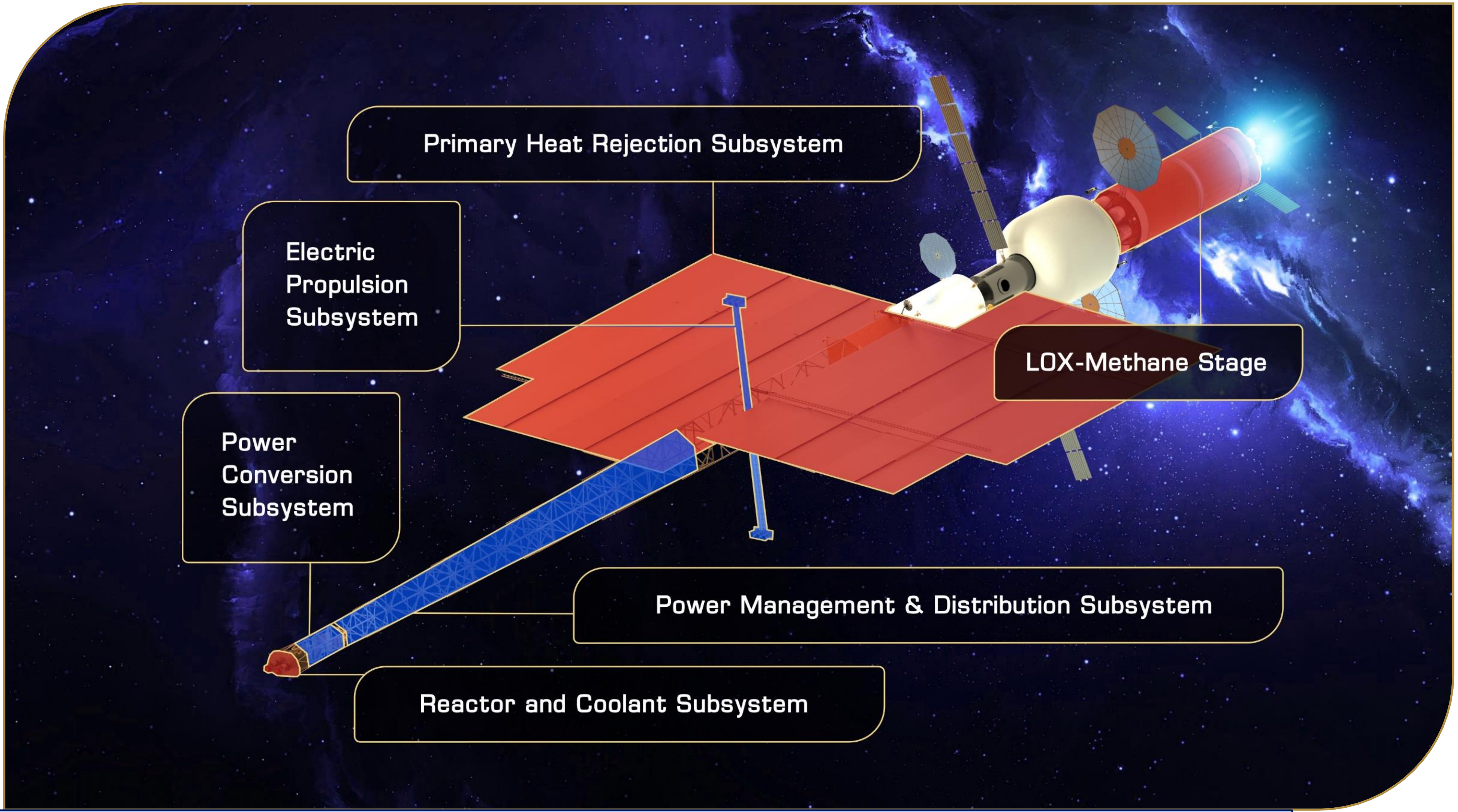
External Partner

- Advising
  - Radiator panel design
  - Material compatibility
- Generated a heat pipe model to be used for radiator panel criteria down select
  - Reported predicted temperatures for the designs
  - Evaluate different designs for heat pipes and radiator panel
  - This model will be used for identifying requirements for the radiator panels
  - Cold start up process for the radiator panels and fluid loop
- Research potential Heat Pipe/Fluid Loop (HP/FL) interface design (new SOW Mod)
  - There is a material compatibility issue at this interface
  - Look for a more efficient, less mass, and less volume design
- Future: Manufacture high-temperature fluid interface mockups
  - Will include both fluid and mechanical components

Hybrid Nuclear Electric Propulsion (NEP)/Chemical Vehicle

Hybrid NEP/Chemical Vehicle Critical Technology Elements:

- Reactor and Coolant Subsystem
- Power Conversion Subsystem (**Brayton Engine**)
- Power Management & Distribution Subsystem
- Electric Propulsion Subsystem
- Primary Heat Rejection Subsystem
- LOX-Methane Stage
  - Not considered a Critical Technology Element since other options are a possibility



We have been using this concept so that we can communicate topics related to how the Primary Heat Rejection Subsystem (PHRS) is part of the Mars Transit Vehicle and to conduct initial studies.

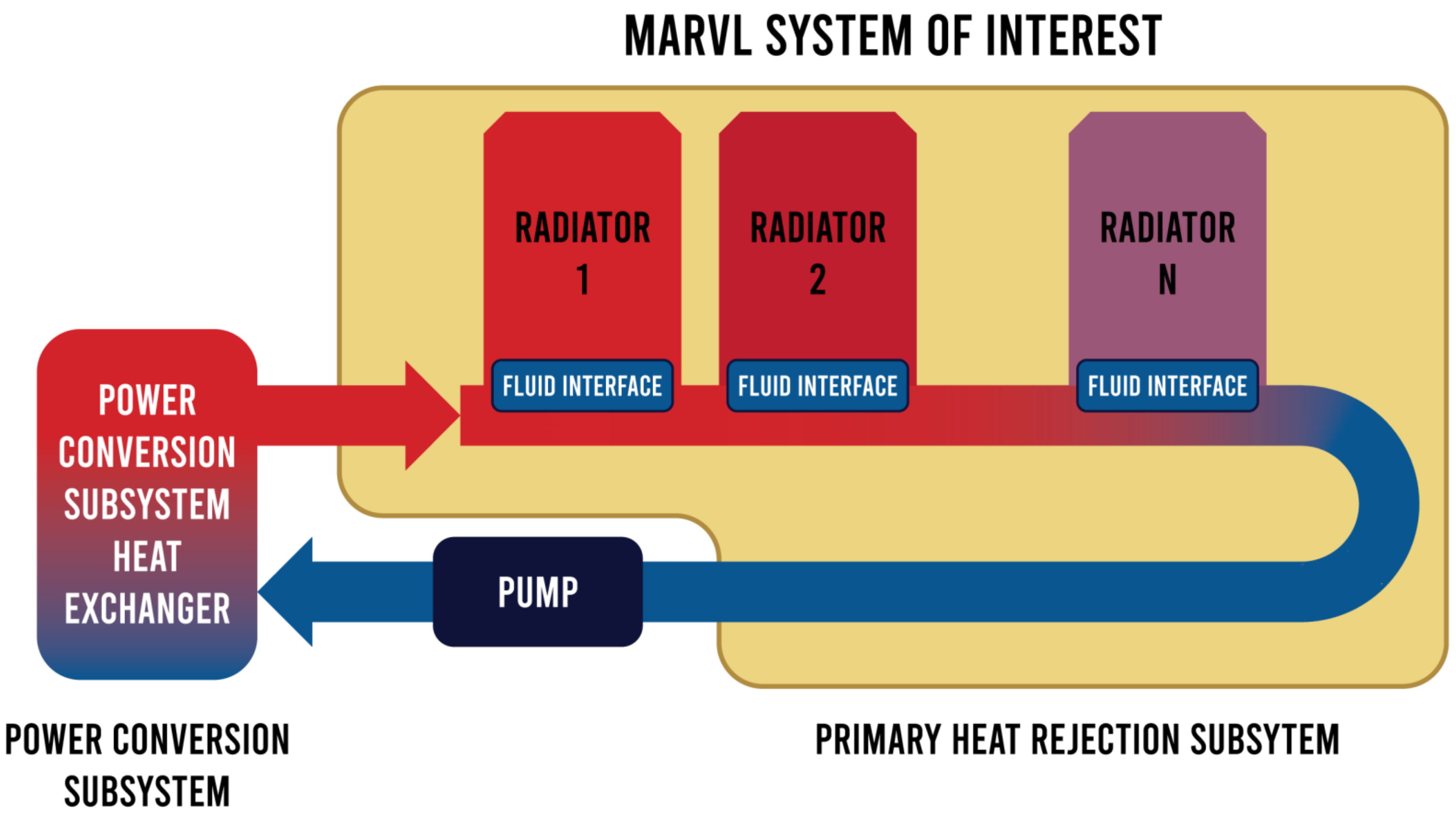
Note: The NEP System of Spacecraft shown is an artist's rendition of the crewed version with one EPS propellant stage. The vehicle configuration and number of elements changes throughout the Mars Opposition Class mission. One possible set of subsystem placements is shown and is subject to change.

Primary Heat Rejection Subsystem

- ***The Primary Heat Rejection Subsystem (PHRS) is the largest and most massive NEP element*** due to the large amount of reactor waste heat:
  - Radiative surface area greater than **3,000 m²** (over half a football field for ~2MWe)
  - Constitutes **40% to 60%** of the total NEP dry mass

- Three key PHRS functions; (1) accept waste heat, (2) transport waste heat, and (3) radiatively reject waste heat to space

- MARVL System of Interest (SoI): Fluid Trunkline, fluid interfaces between Trunkline and radiators panels, Radiator Panels



Radiator Unit Options

Radiator Panel: a collection of heat pipes between two radiator facesheets

Panel Set: a set of two or more radiator panels connected with a fluid loop and structural support

Module: two or more Panel Sets

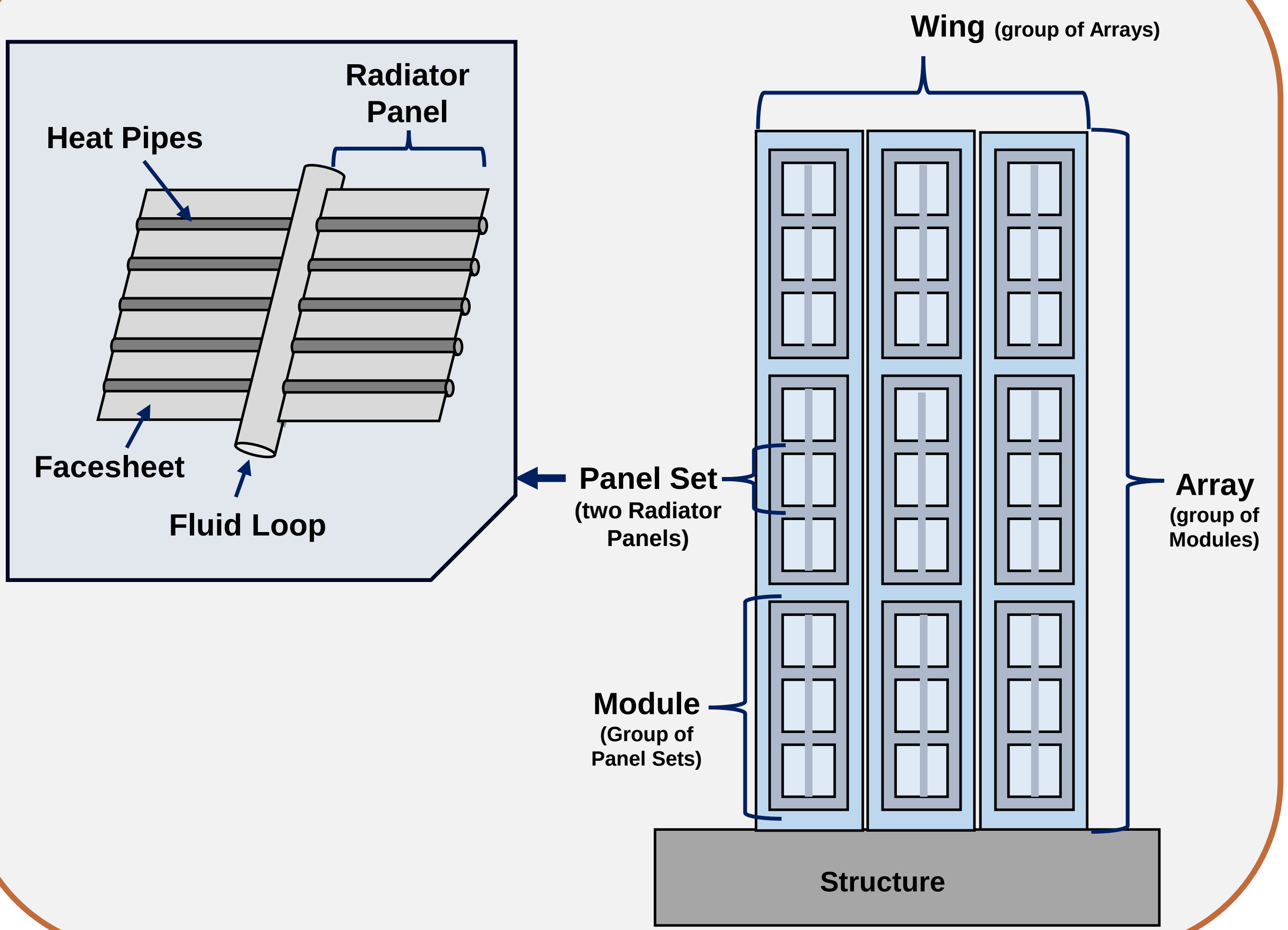
Array: a group of two or more Modules

Wing: a group of two or more Arrays

Other System Definitions:

- **Installation:** incremental assembly/deployment of the PHRS radiators prior to reactor startup
- **Commissioning:** achievement of an operational PHRS in-line with reactor startup

MARVL Radiator Terminology



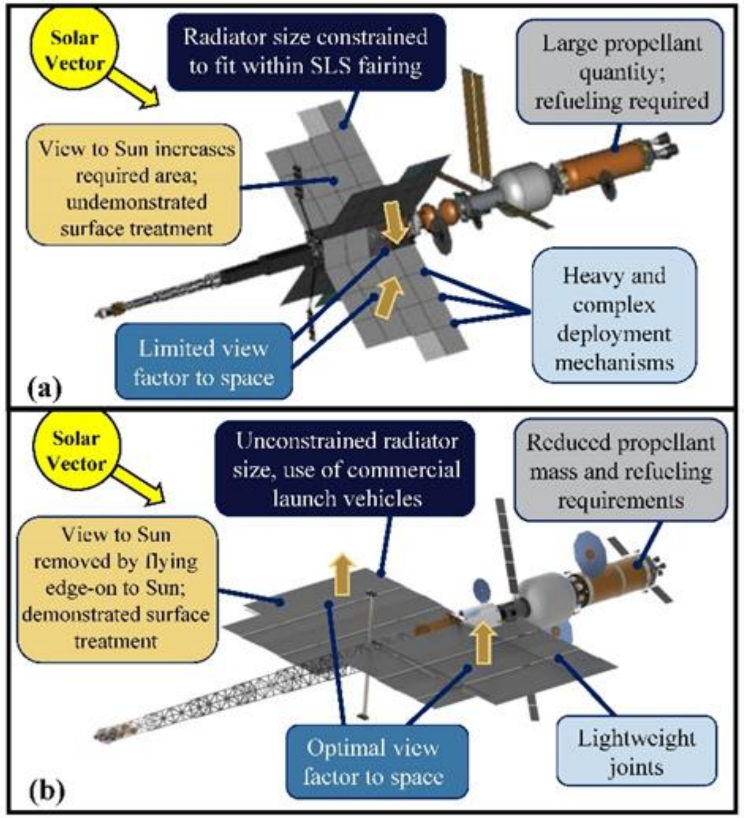
Incorporating in-Space Assembly

Vehicle	Vehicle Length	Radiator Area
NEP	~100 to 150 m	~3000 m^2

Flight orientation results in view factor losses which increases mass

~25% decrease in radiator mass due to reduced area from flying edge onto Sun.

- Use of in-Space Assembly (iSA) in designing NEP modular radiators has the potential to improve overall vehicle performance while reducing mass, schedule, cost, and risk.
- Enables (1) mass-efficient bi-wing design, (2) architectural flexibility, and (3) use of commercial launch vehicles



Quad-Wing (a) vs Bi-Wing (b) Configurations

Need-Goal-Objective (NGO) and KPP

Need	Large-scale in-space radiator technology that meets launch vehicle constraints, reduces system mass, improves system performance, reduces risk, and provides future mission planners flexibility in NEP architecture design			
Goal	Design and analyze a lightweight PHRS targeting an NEP capability			
Objective	Define and evaluate a set of PHRS installation and commissioning concepts	Build an integrated simulation to predict and analyze system behavior in relevant environments	Define and analyze a representative modular high-temperature radiator unit design	Define and analyze a high-temperature fluid interface design
Success Criteria	A quantitative analysis framework capable of informing the selection and refinement of a PHRS design by estimating design feasibility, vehicle performance, development and production cost, mission risk, in-space logistics, and launch packaging	Integrated simulation to guide PHRS design and support future hardware-in-the-loop testing. Framework will consider environmental impacts on thermal and structural design integrity during critical commissioning operations	Radiator unit design that enables PHRS commissioning with a minimum total power ratio level of 1.5 MWth/MWe, maximum operating temperature of ~550 Kelvin, and an areal density of ≤ 4.5 kg/m^2	High-temperature fluid interface design that operates at 550 (inlet) and 450 (outlet) Kelvin, up to 500 kPa working pressure, with a NaK flow rate up to ~30 kg/s, while enabling in-space commissioning of radiator arrays

MARVL Key Performance Parameter (KPP)

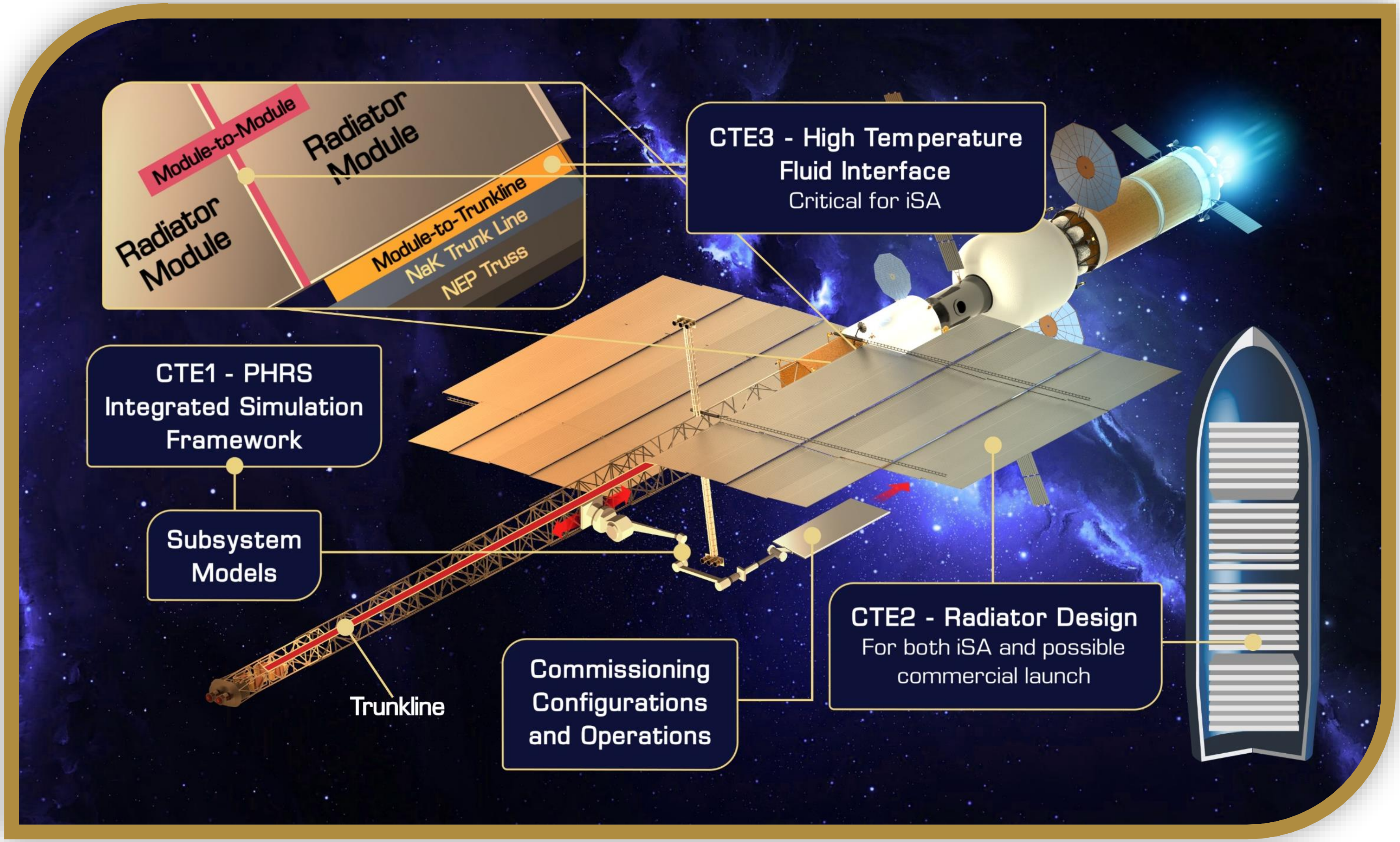
Title	Description	Unit	SoA	Threshold	Goal
PHRS specific mass (α)	PHRS mass per unit electrical power produced by nuclear reactor	kg/kWe	~11*	8†	3.5‡

*ISS Radiators (used as panel analogy only – deployment and trunkline similar to published NEP concepts) at 2500m^2 for 2MWe NEP; † 25% α reduction; ‡ 65% α reduction; SoA with deployment mechanisms at an areal density of 3.5 kg/m² is 16 kg/kWe

MARVL Critical Technical Elements

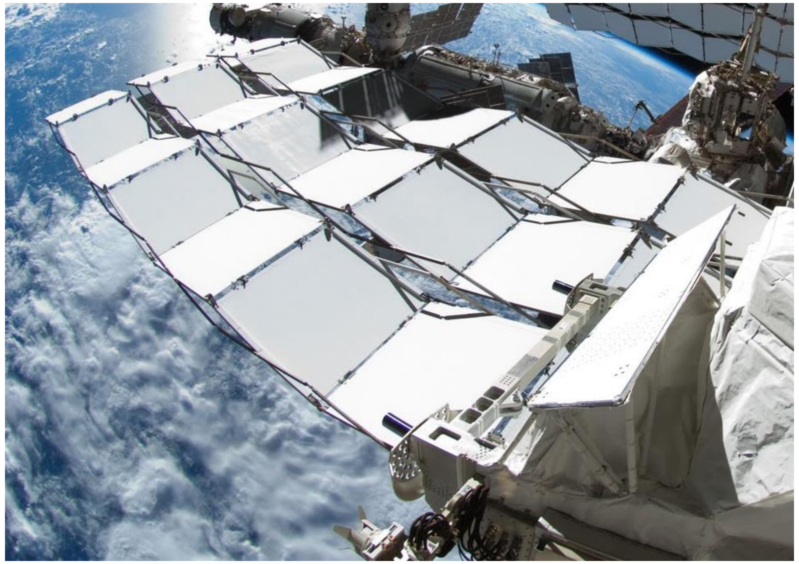
Critical Technical Elements (CTE):

- CTE1 – PHRS Integrated Simulation Framework
- CTE2 – Radiator Design
- CTE3 – High Temperature Fluid Interface



State of the Art - ISS Radiators

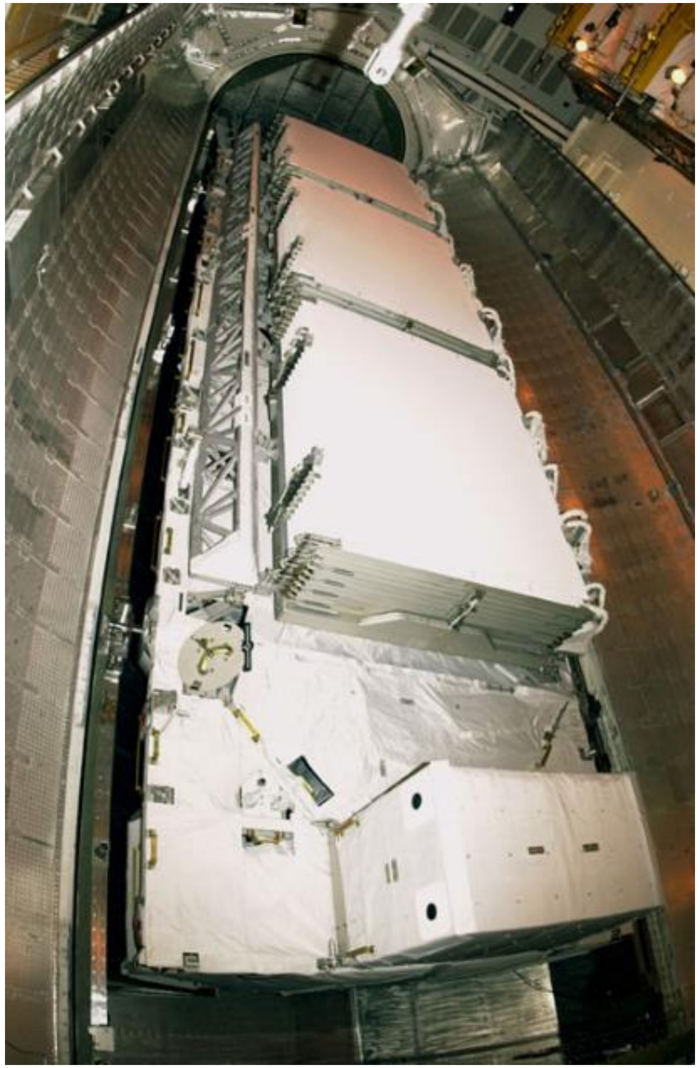
- The International Space Station (ISS) Active Thermal Control System (ATCS) radiator arrays, with their Orbital Replacement Unit (ORU) interfaces, are the most relevant state of the art in terms of size and commissioning approach
  - ISS radiator arrays were launched in several segments, robotically assembled on orbit, then remotely deployed
  - Six radiator array modules were attached to the central truss, including installation of structural, fluidic, and electrical connections
  - However, ISS radiators do not meet NEP PHRS requirements



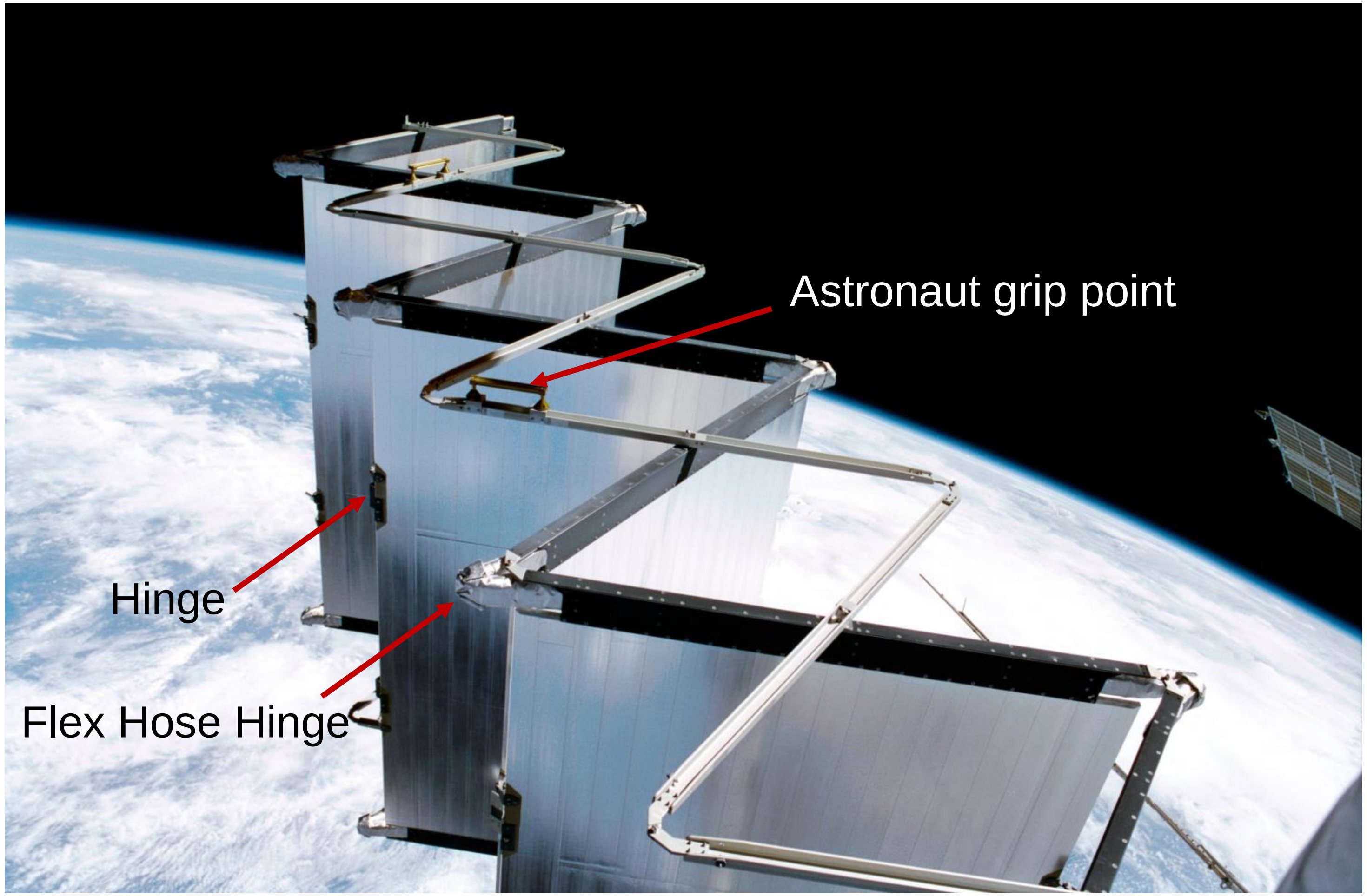
System Characteristics: ISS Radiators vs MARVL PHRS

System/ Characteristic	ISS Radiator Arrays	MARVL PHRS
Commissioning Method	Robotically Installed & Deployed	Robotically Installed & Deployed or Fully Assembled
Surface Area	~1300 m²	>3000 m²
Launch Vehicle(s)	~5 Space Shuttles	TBD
Thermal Working Fluid	Anhydrous Ammonia	Liquid Metal NaK
Fluid Temperature	~300 K	~550 K
Areal Density	~7.0 kg/m²	<4.5 kg/m²
Heat Rejection	~125 kW	~4 MW
Design Environment(s)	LEO ~400 km altitude ISS Interfaces	Mars Opposition Class Mission NEP/Chem Vehicle Interfaces

State of the Art – ISS Radiators

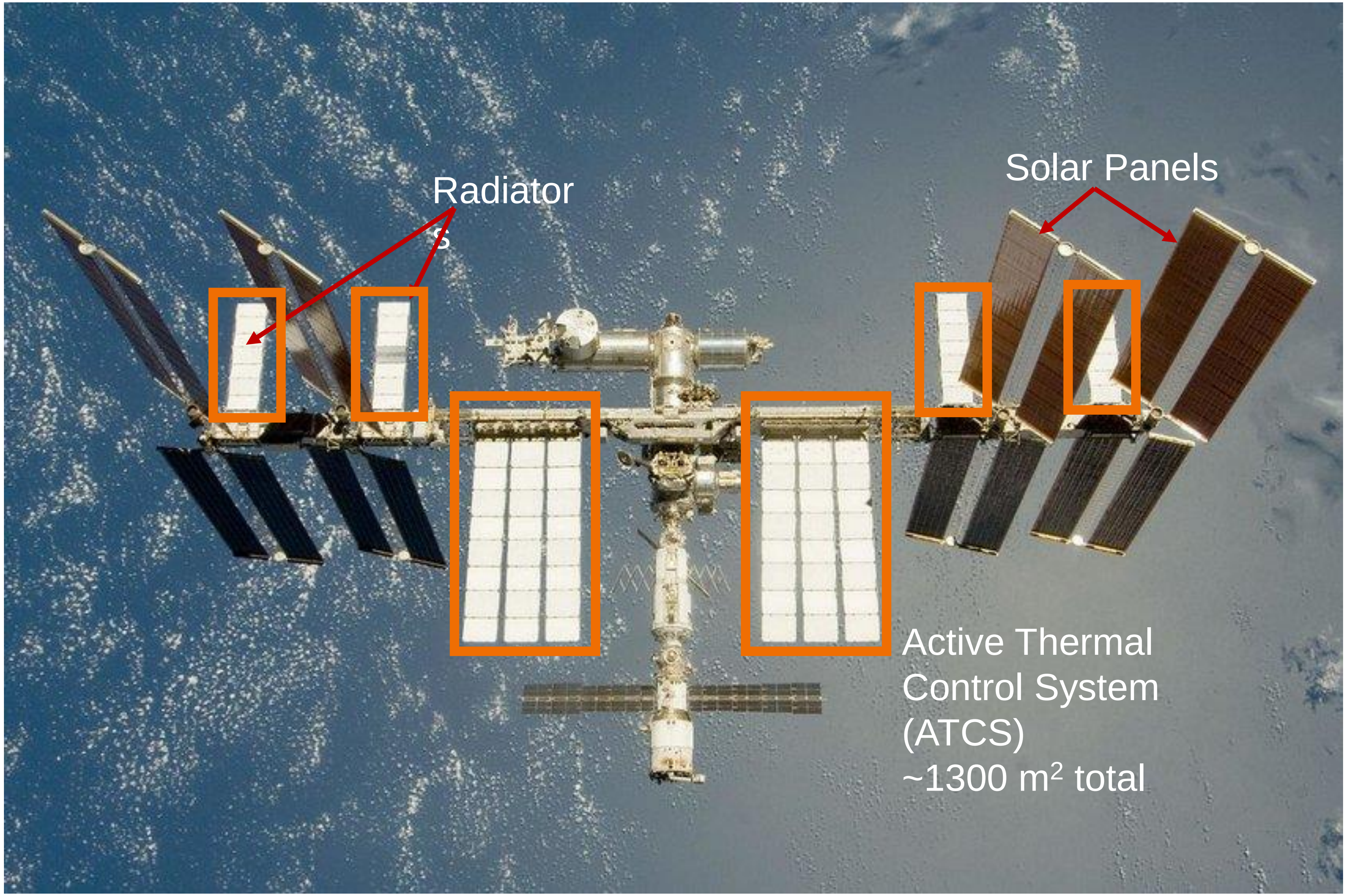


Radiator Unit Stowed in the Space Shuttle for delivery



ISS Scissor Truss or Pantograph Design

State of the Art



Gaps Being Addressed

STMD Shortfall Select List

Title	Rank	Capability	Applicability	Justification
1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation	5	Autonomous Systems and Robotics	Primary	Design and analysis of NEP PHRS architecture and operations with maximized capability as well as astronaut time and safety
709: Nuclear Electric Propulsion for Human Exploration	8	Propulsion: Nuclear	Primary	
1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions	18	Autonomous Systems and Robotics	Primary	
1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization	65	Autonomous Systems and Robotics	Primary	
1619: High temperature heat rejection for nuclear applications	82	Thermal Management Systems	Primary	
376: Modular design for in-space installation	109	ISAM and RPOC	Primary	
1540: Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets and Industrial-Scale Surface Infrastructure	133	Autonomous Systems and Robotics	Primary	
513: Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure	153	ISAM and RPOC	Primary	

Moon2Mars Architecture-Driven Technology Gaps

Title	Priority Rank	Priority Bin	Applicability	Justification
1104: Mars Transportation Propulsion	4	1	Primary	Design and analysis of NEP PHRS architecture and operations with maximized capability as well as astronaut time and safety
1003: Integrated System Fault/Anomaly Diagnosis, Decision Support, and Response	18	3		
1005: Safe Human-Robot Interaction and Teaming	27	3		
1004: Trustworthy Autonomy for Planning and Decision-Making	30	4		
1002: Autonomous Monitoring for Exploration Missions	31	4		
0501: Robotic and Human-Robotic Inspection, Maintenance, and Repair	33	4		

Stakeholder and Community

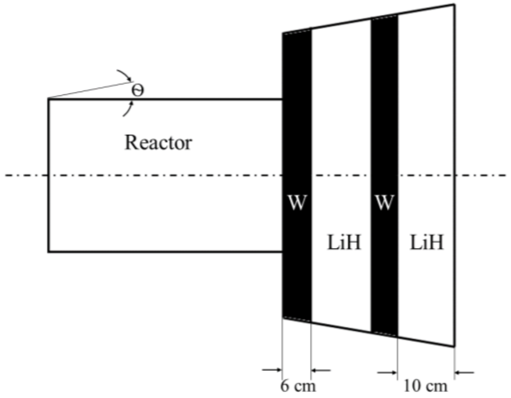
- Space Nuclear Propulsion Program: Main Stakeholder
  - Hold monthly meeting with key engineers involved in the program
  - Invite key engineers to DAC sync and project reviews
- Alternate/other stakeholders:
  - STMD (PTs, ECI, TMD)
  - Moon 2 Mars
  - Space nuclear private industry – contact mostly made at conferences and workshops
  - Fission Surface Power
  - Lunar or Mars habitats that require high power - high temperature radiators or iSA
  - LEO or Lunar orbital space stations - high temperature radiators or iSA
- The team has worked to engage with the nuclear community through in-person meetings at conferences, but with travel still being difficult, in-person meetings have been out of reach

In-Space Assembly Design Space and Modularity

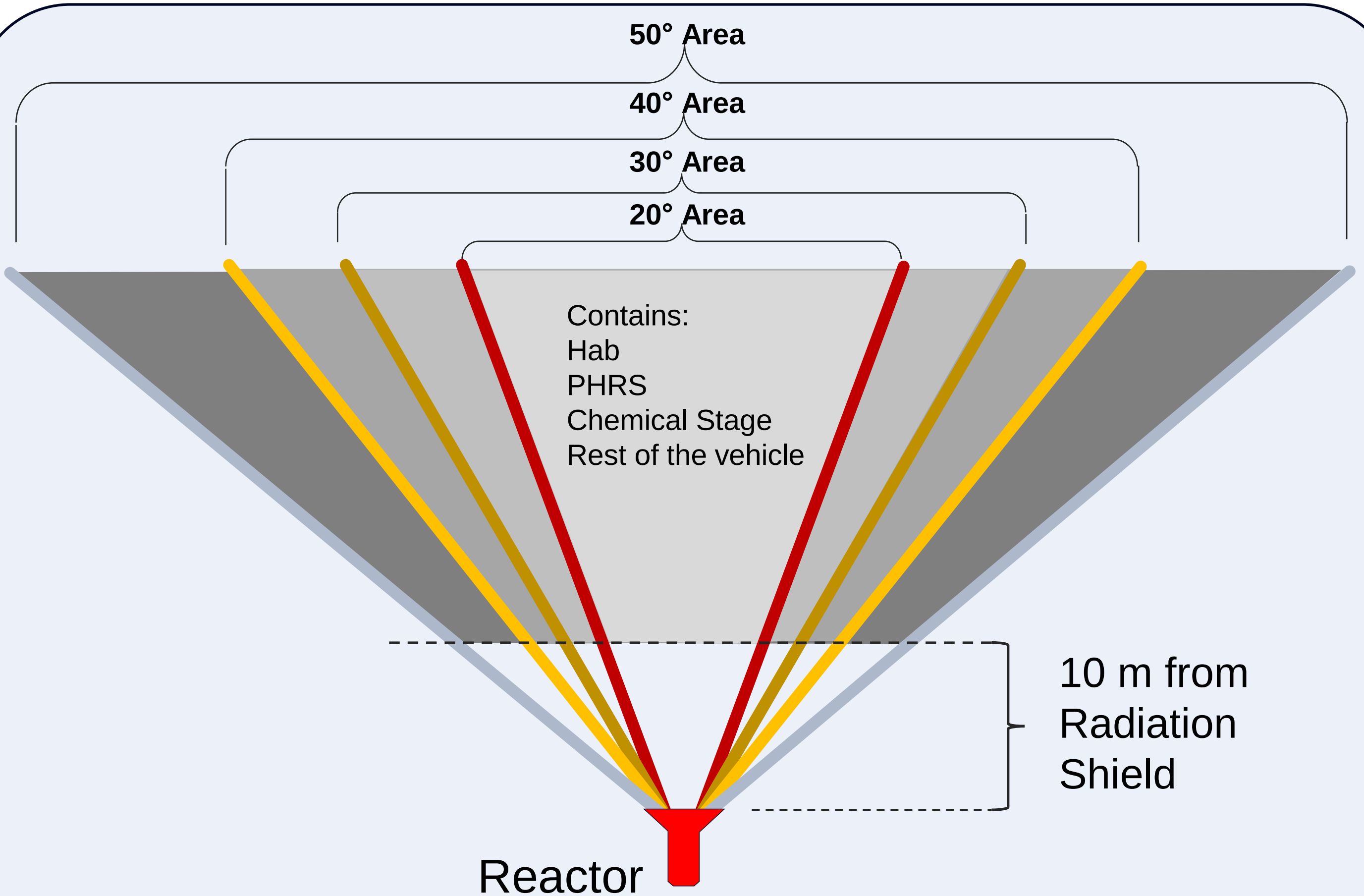
Design Space for the Required Radiator Area

- Design space driven by:
  - Reactor shield cone angle/shape
  - Structure Length

- Design space drives the:
  - NEP system mass
  - Available radiator volume
  - Available robotic workspace



Shield Material Layup



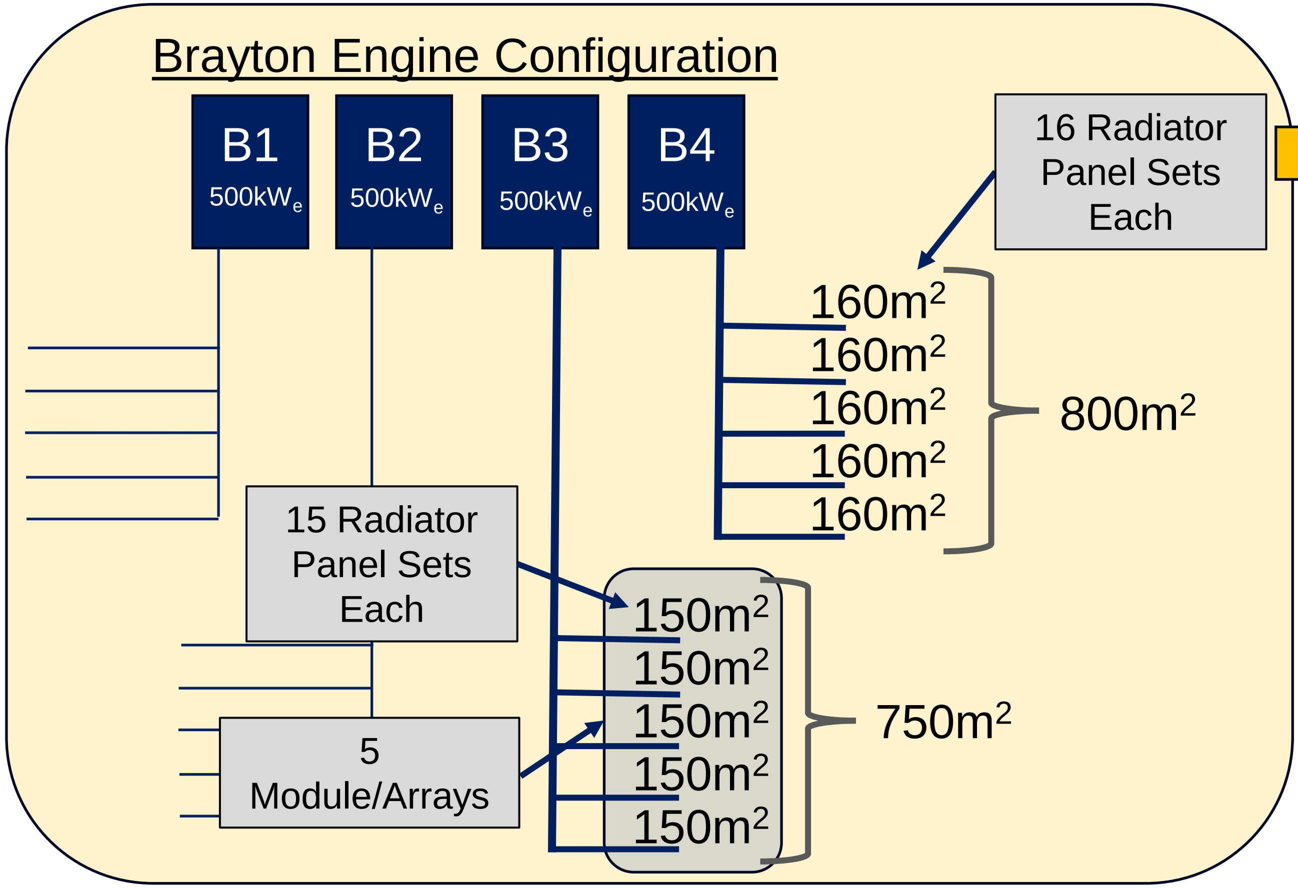
Radiation Shield Angle options with Design Area Indicated

Power Generation versus Waste Heat

Power generation from the Power Conversion Subsystem 2 MW_e

Waste heat transported to the PHRS ~4 MW_{th}

Estimated radiator area 2000 to 4000 m^2



Potential Modular Unit

Radiator Panel = 2.5mx1.0m = 5m^2 (double sided)

Panel Sets= 2.5mx2.0m = 10m^2 (double sided)

Module or Array = 10m^2 (double sided) x 16 = 160m^2

R1	R3	R5	R7	R9	R11	R13	R15
R2	R4	R6	R8	R10	R12	R14	R16

Total Area = 750m^2 x 4 = 3000m^2

Total Area = 800m^2 x 4 = 3200m^2

Three Potential Reference Configurations

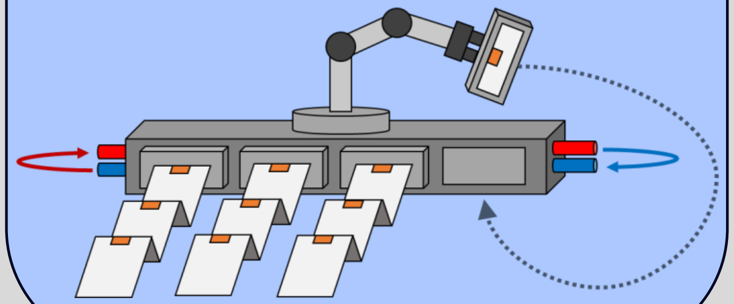
Legend

- In-Space Assembly Interface
- Deployment Mechanism
- Thermal Working Fluid (cold & hot)
- Radiator Panel with Heat Pipes

Current MARVL Focus

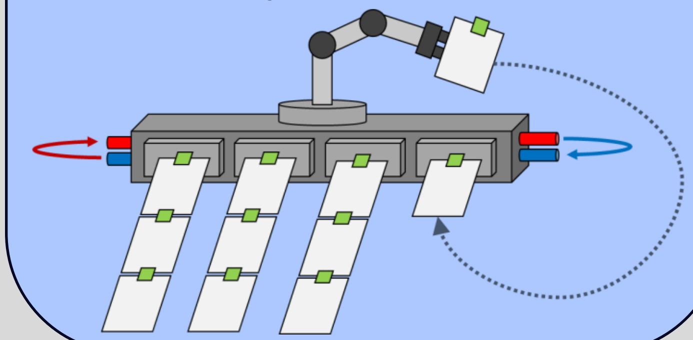
Hybrid

- Robotically assembled/installed units which are then deployed
- Exploring hard mounted and mobile robotic agents
- Requires multiple launches
- Enables architectural flexibility and extensibility



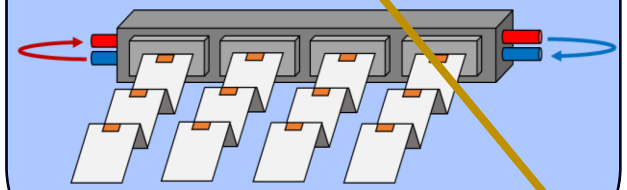
Full Assembly

- Radiator units are robotically assembled into configuration
- Exploring hard mounted and mobile robotic agents
- Requires multiple launches
- Enables architectural flexibility and extensibility



Full Deployment

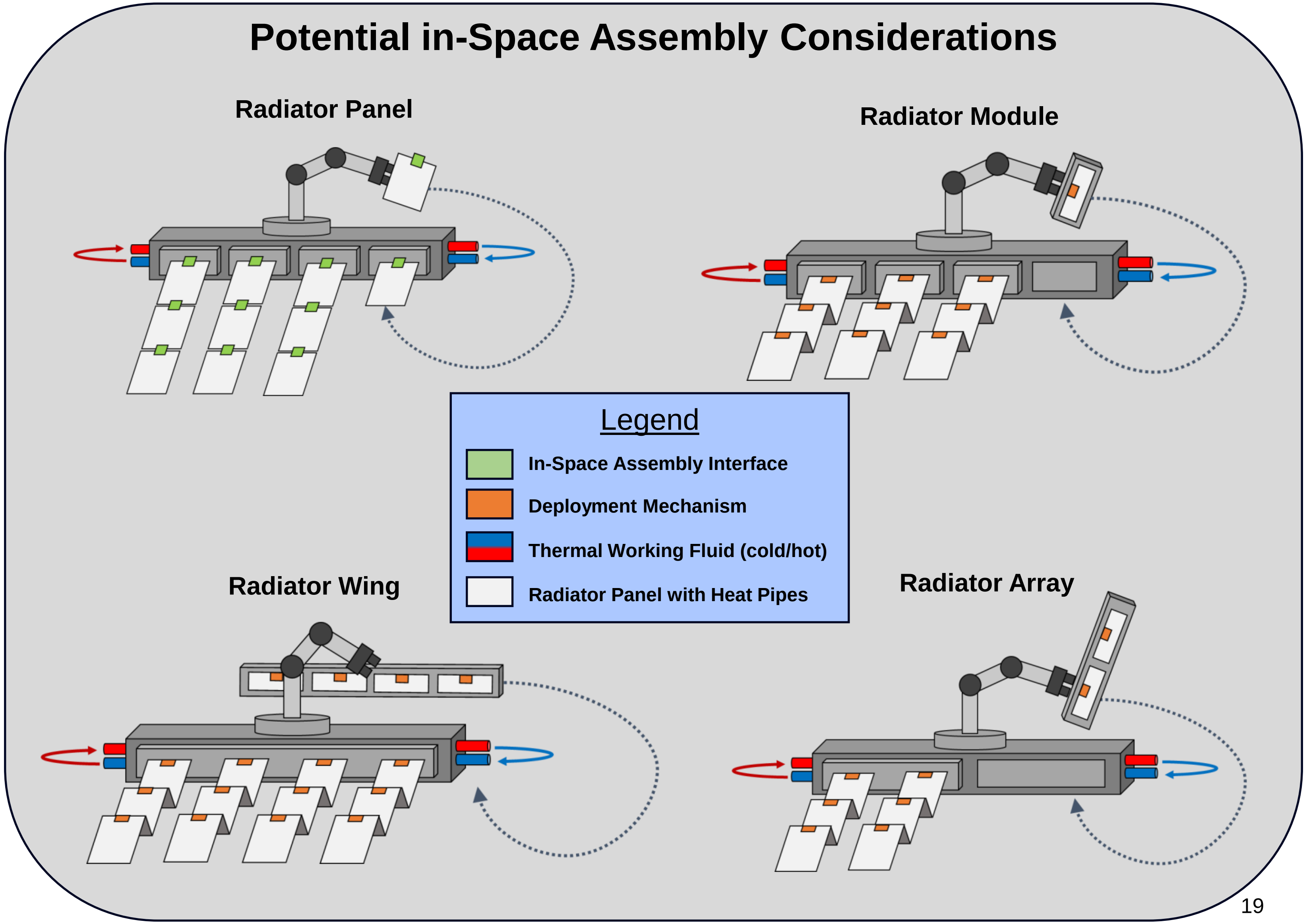
- ISS heritage mechanisms assumed
- Single-launch
- Enough volume on New Glenn, Starship, or SLS Cargo fairing with >>30% margin



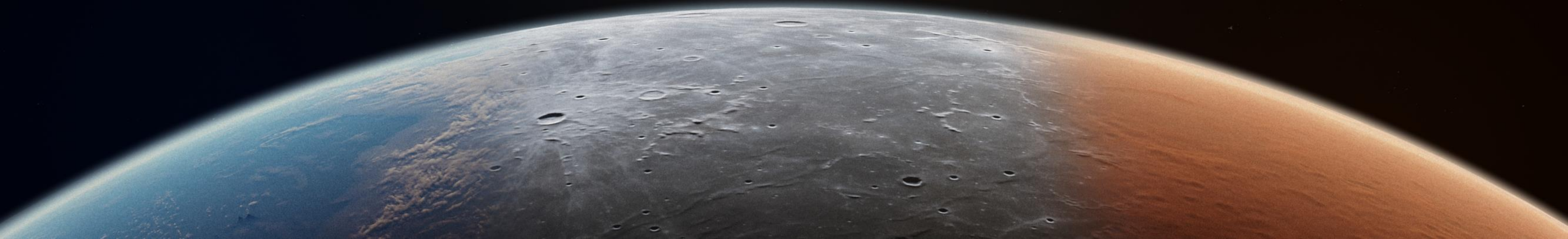
ISAM = In Space Assembly and Manufacturing   ISS = International Space Station   SLS = Space Launch System

iSA Radiator Modular Units

In-Space Assembly opens the design space to consider what a modular unit could be



Mars Mission Environment

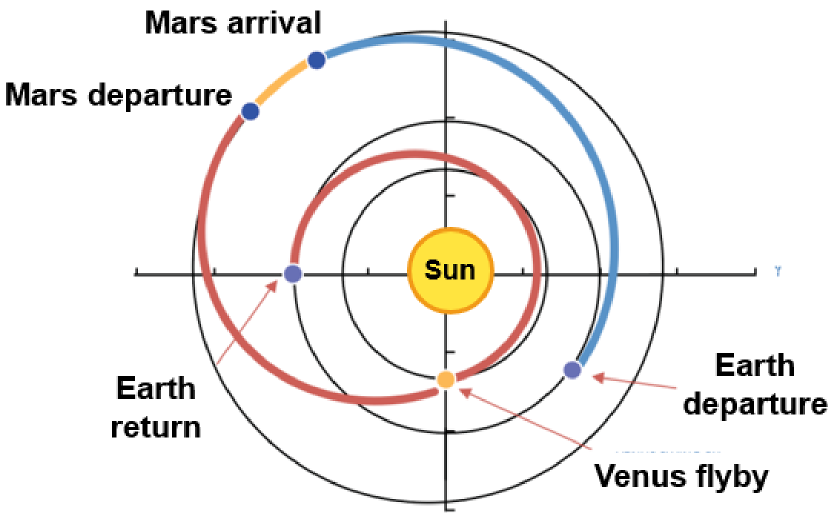


Enveloping Mars Mission – Environmental Modeling

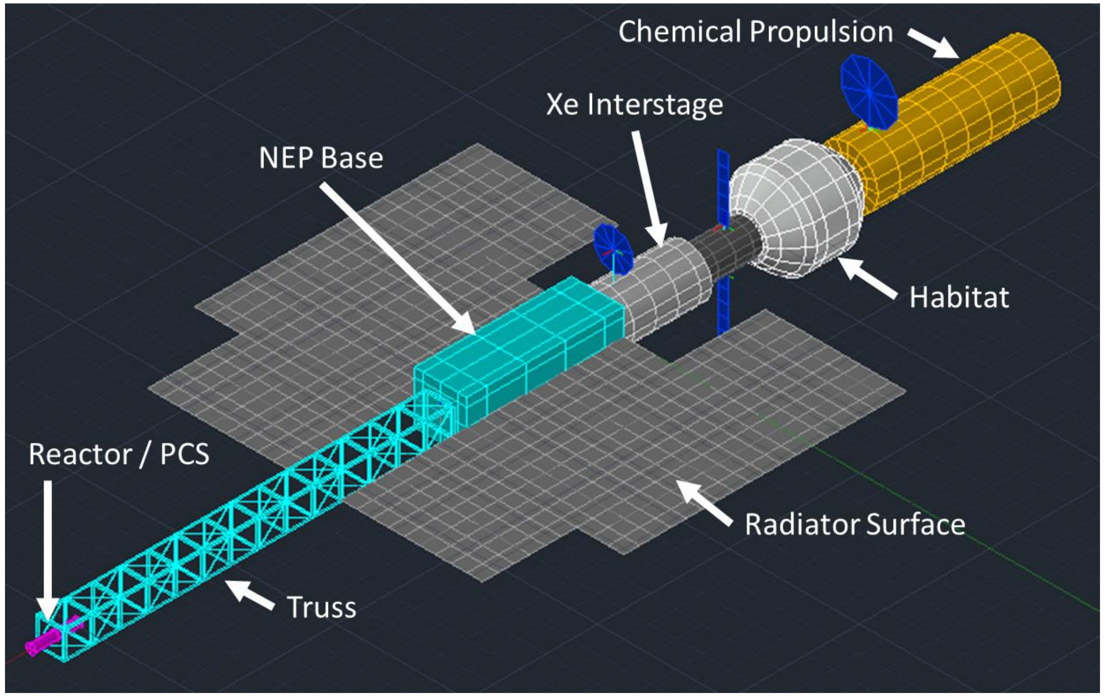
- The target application for technology development is a Crewed NEP Mars Opposition Class Mission:
  - Crew departure date: 2039
  - Total mission duration: ~3 years
  - Hybrid NEP/chemical vehicle (NEP for cruise phases & chemical stage to enter/exit gravity wells)

Possible locations: Low Earth Orbit, Near Rectilinear Halo Orbit, Lunar Distant High Earth Orbit, Interplanetary, Mars Orbit, Venus Flyby

Relevant Environments: thermal, vacuum, Micro Meteoroid and Orbital Debris (MMOD), radiation, launch loads, in-space loads, microgravity



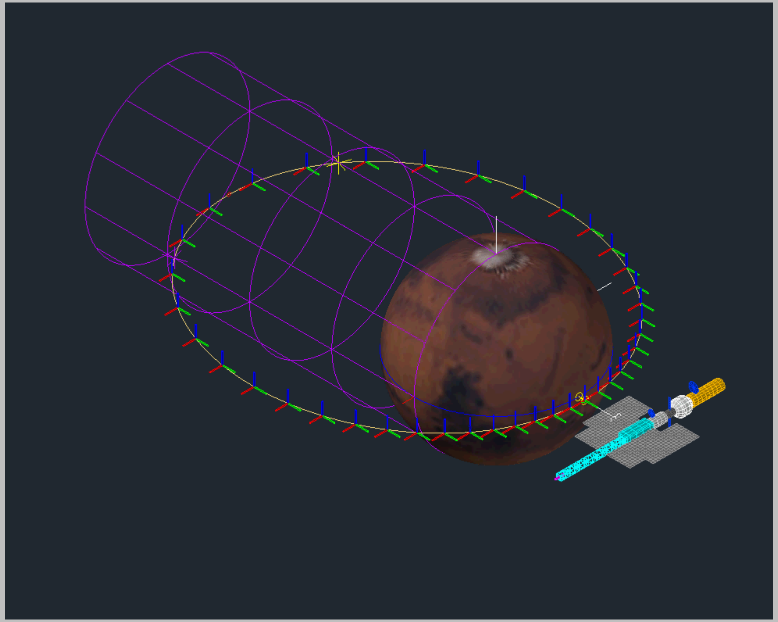
Opposition Class Mission



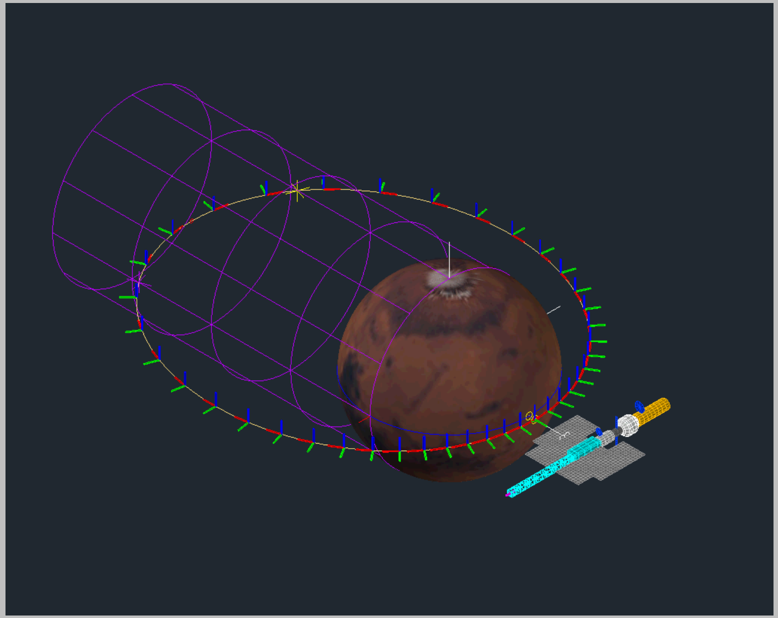
Thermal Desktop Model for the NEP Vehicles

Full Vehicle Model - Pointing Cases

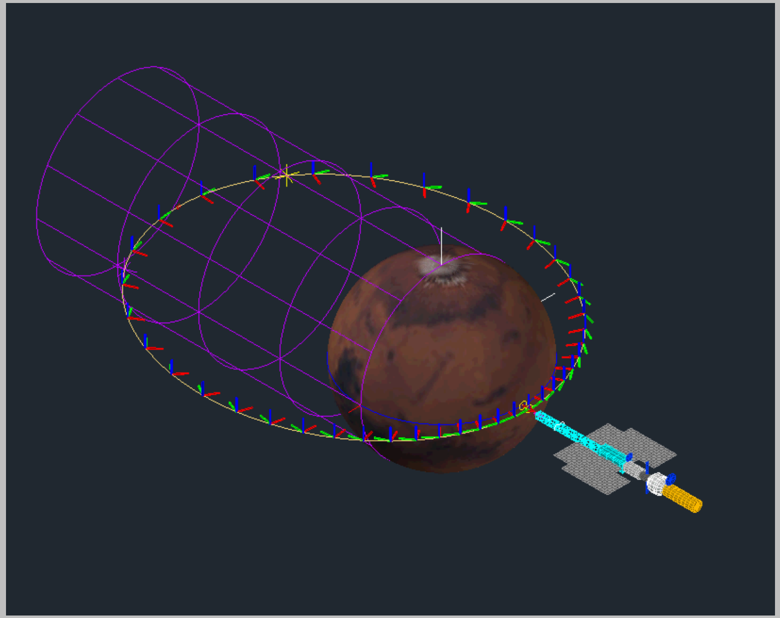
- Sink temperature and heat rejection capability curves gathered for 41 cases from a simplified plate model in addition to 2 full vehicle orientations (reactor to velocity vector and reactor to planet)
  - 3 total pointing configurations assessed (applied via trackers in Thermal Desktop)
  - 88 total cases evaluated for the full vehicle model (face to sun orientations do not require R2VV or R2P pointing)



Same as plate model, does not change pointing during orbit



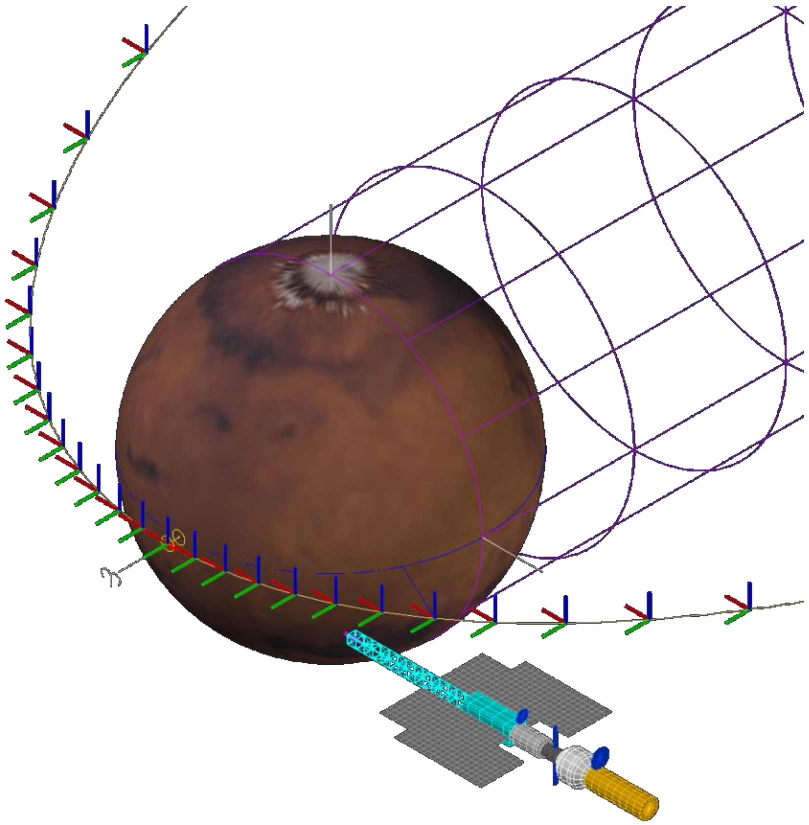
Reactor to Velocity Vector (R2VV)

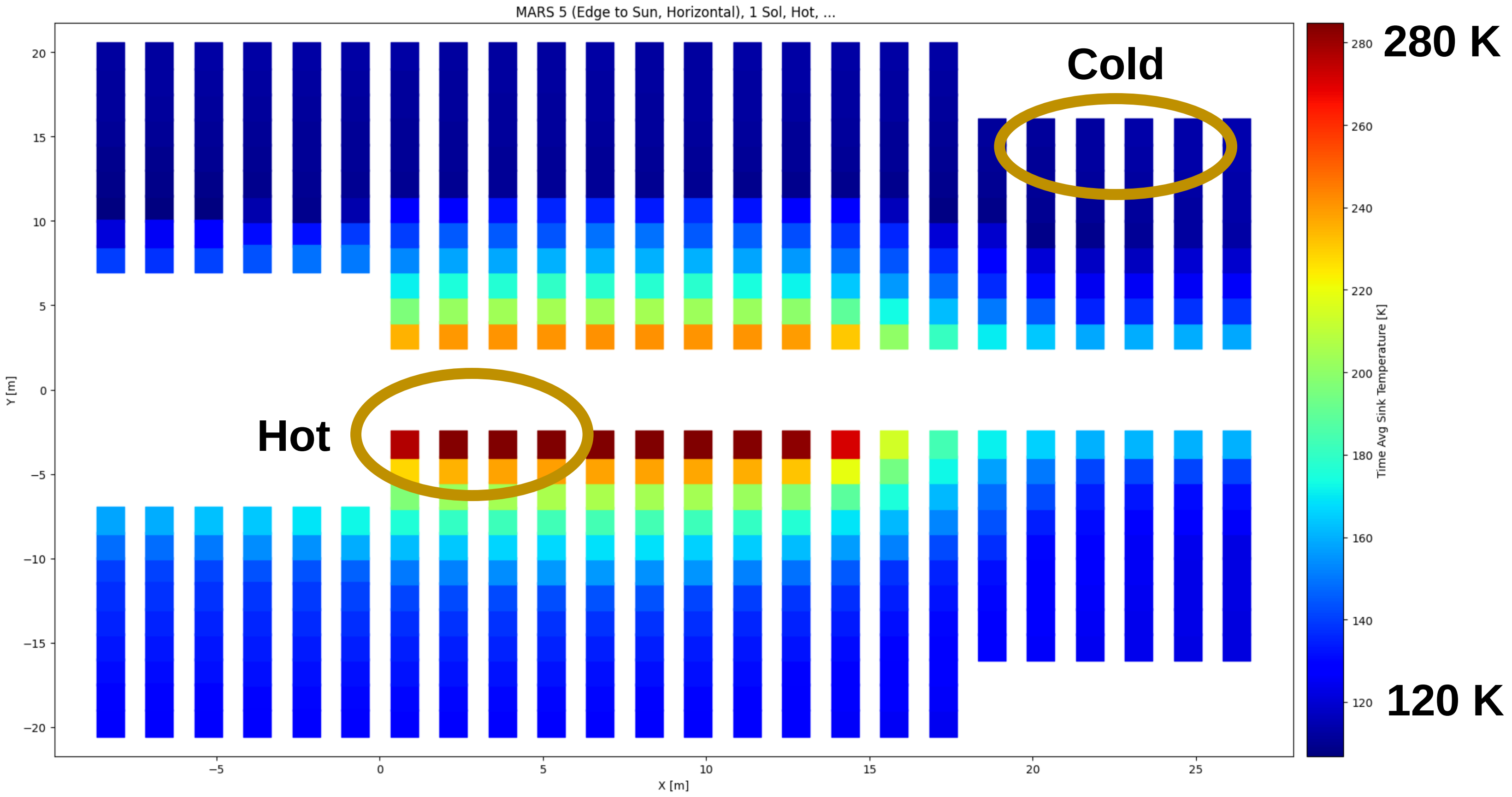


Reactor to Planet (R2P)

Pointing Effects

- Due to reflections and shadowing, the Full Model is pointing dependent leading to a non uniform sink temperature distribution across the panels
  - "Hot Spots" occur on radiator surfaces near adjacent spacecraft elements





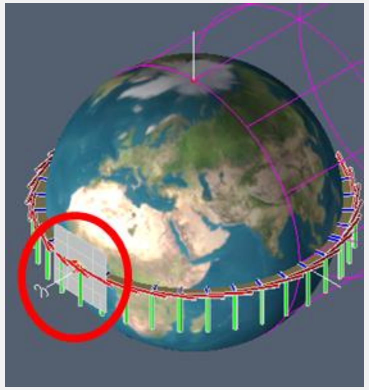
Radiator Nodal Sink Temperature

Worst Cases - Plate and Full Vehicle Models

- **41 and 88 viable model cases (plate and full vehicle model) <u>reduced to 6</u> hot and cold extrema cases**
  - A decision on the installation and commissioning orbit has yet to be made (500 km LEO, 1100 km LEO, or NRHO)
  - All reported vehicle sink temperatures are an average of all radiator nodes, single nodes in the full vehicle model experience large differences
  - The simple plate model is a good approximation (+/- 8% heat rejection capability) and radiator properties can be varied parametrically

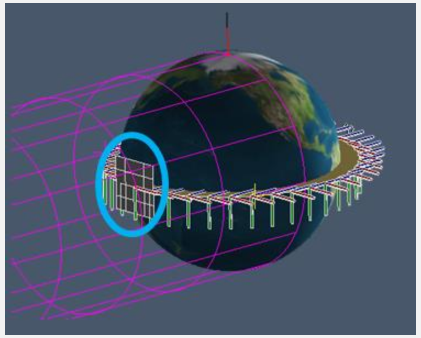
Reactor powered OFF

Max
Vehicle = 300 K
Plate = 298K



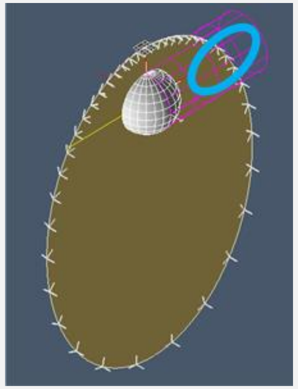
LEO, 500 km altitude
0˚ beta angle
Face to Earth, Edge to VV
Position: subsolar point
Vehicle Pointing: N/A

Min
Vehicle = 169 K
Plate = 157 K



LEO, 1100 km altitude
52˚ beta angle
Face to Sun
Position: within shadow
Vehicle Pointing: N/A

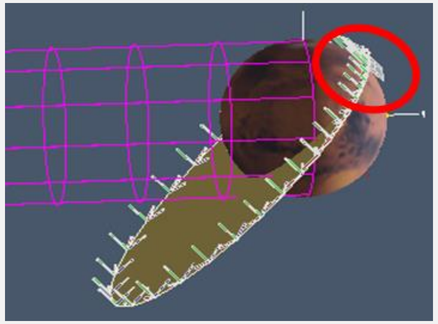
Min
Vehicle = 123 K
Plate = 30 K



NRHO
0˚ beta angle
Face to Sun
Position: within shadow
Vehicle Pointing: N/A

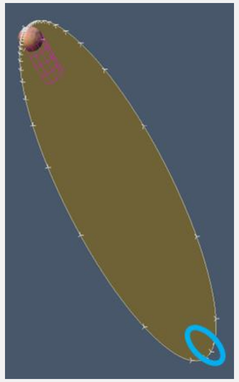
Reactor powered ON

Max
Vehicle = 250 K
Plate = 237



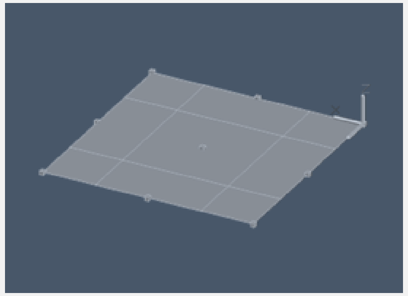
Mars orbit, <1-sol
45˚ beta angle
Edge to Sun (Horizontal)
Position: periapsis
Vehicle Pointing: R2VV

Min
Vehicle = 122 K
Plate = 5 K



Mars orbit, 10-sol
0˚ beta angle
Edge to Sun (Horizontal)
Position: apoapsis
Vehicle Pointing: N/A

Min
Vehicle = 55 K
Plate = 3 K



Interplanetary Space
0˚ beta angle
Edge to Sun
Vehicle Pointing: N/A

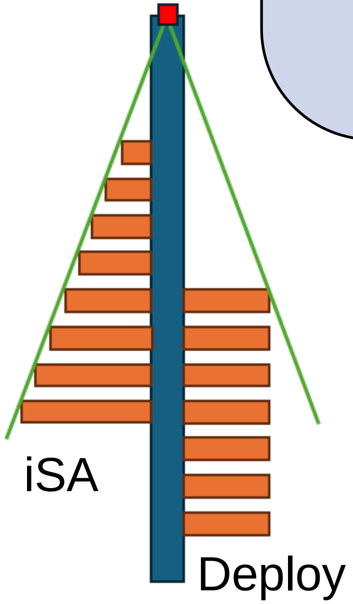
Design Trades and Options

Hybrid vs Full Assembly Overview

- Hybrid considerations include iSA components
  - Current assembly approaches
    - *Panel Set to Panel Set with iSA*
    - *Hybrid using hinges*
    - *Hybrid using pantograph*
  - Two options for Fluid Loop routing
  - Fluid interface shall work for both

	Hybrid - Hinges	Hybrid - Pantograph	iSA
Fluid Interfaces Per Assembly Operation	2	2	2
Number of Assembly Operations	40	40	320
Total Fluid Interfaces	80	80	640*
Flex Hoses per Panel	2	2	0
Number of Panels Sets	320	320	320
Total Flex Hoses	640	640	0
Deployment Mechanism Specific Mass	1	1.12	0

*Count for just Panel Set to Panel Set, this is the maximum



Potential Configuration Differences

Flex Hose Research

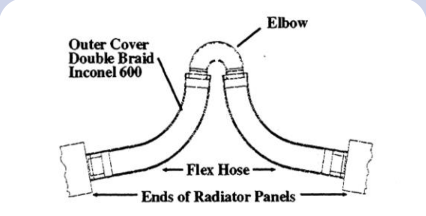


FIGURE 10 FLEX HOSE MICROMETEOROID AND THERMAL PROTECTION

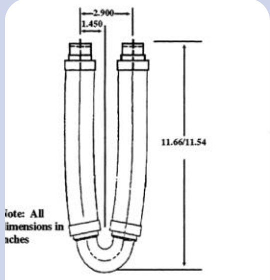
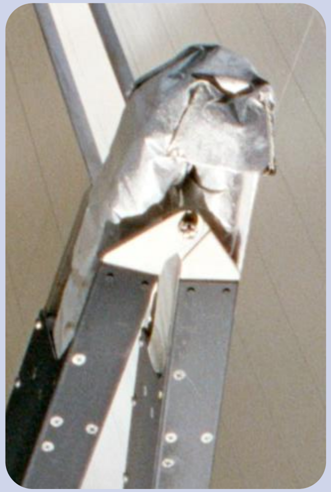
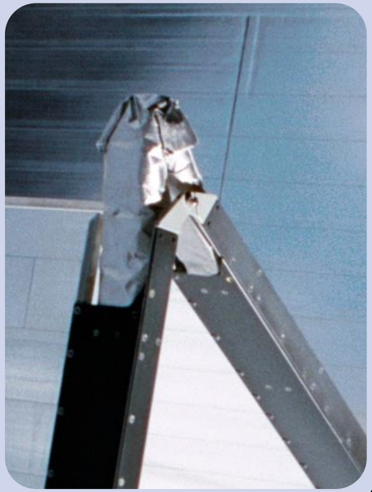


FIGURE 9 STOWED FLEX HOSE DETAIL





Deployment Mechanism

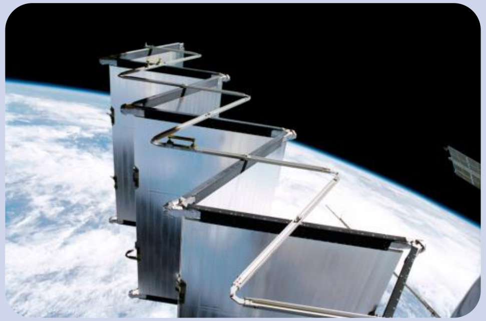
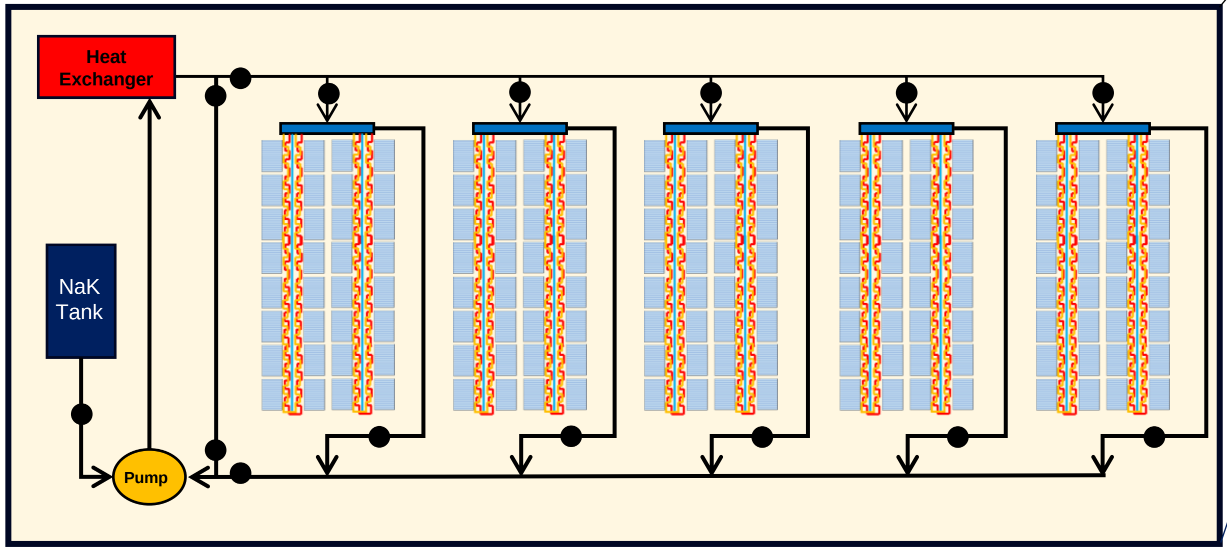


Image Source: Airbus Defense & Space

Brayton Unit Layout

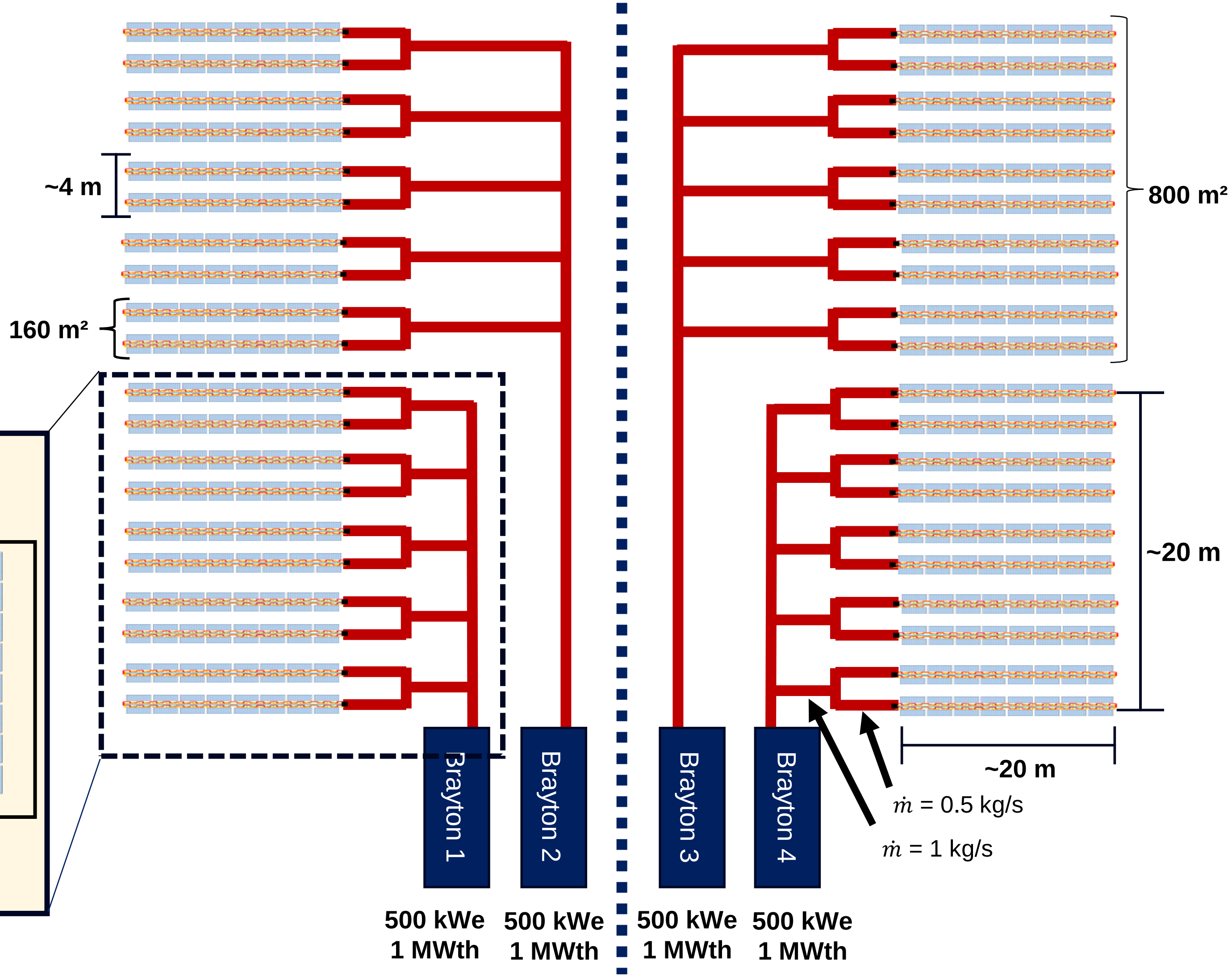
- Potential radiator area configuration
  - Dedicated radiator arrays/wings for each Brayton
  - Total surface area per Brayton 800m^2
    - With this knowledge the panel/panel set/module/array can be situated in the best configuration
- Placement for valves will need to be considered for commissioning (gradual fluid introduction)
- Out of Scope:
  - Location of the Pump and NaK Tank is out of scope
  - Interface at heat Exchanger for PCS



Candidate Brayton Unit Layout

Fluid Interface

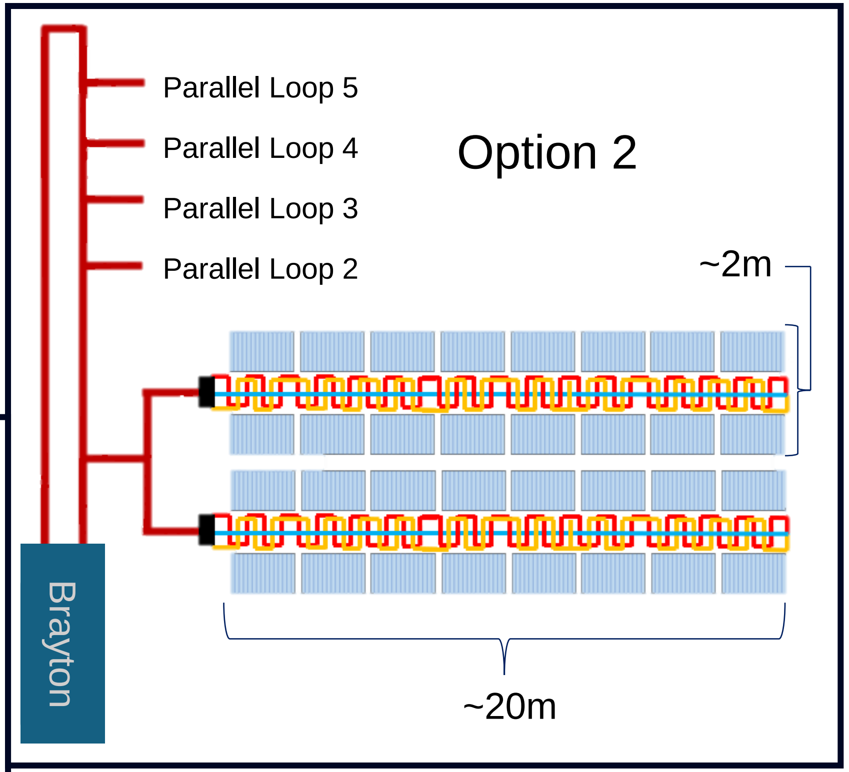
Valve

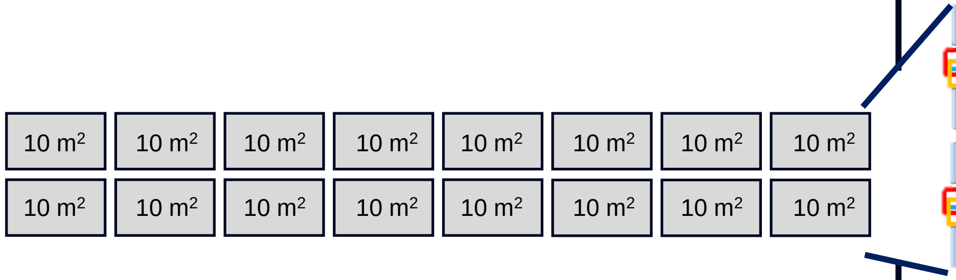


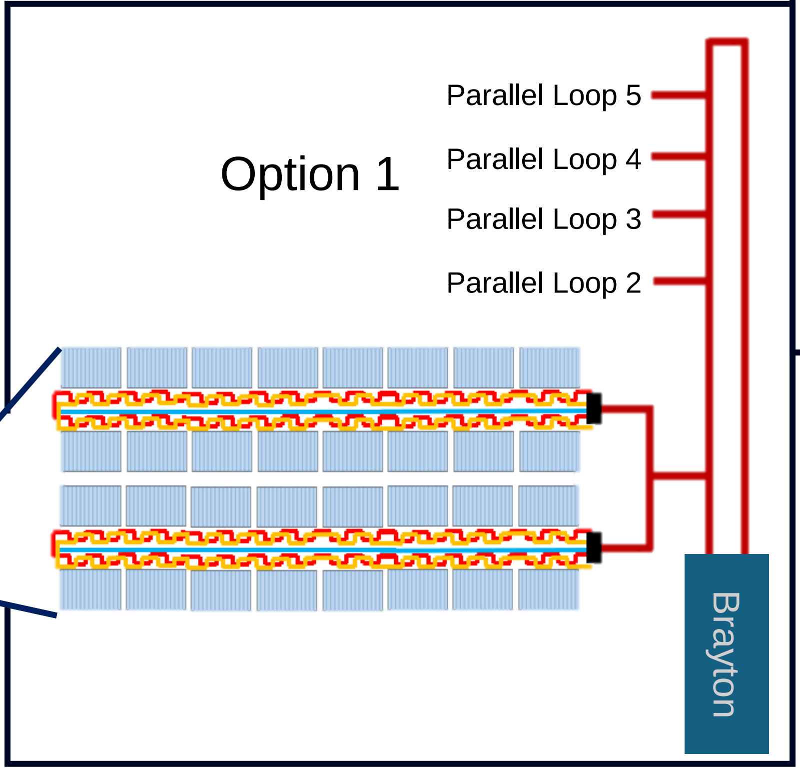
Candidate Layout & Sizing, 4 Brayton Units

Baseline Design for the Fluid Loop

- Baseline design is a 2x8 – 1m x 2.5m radiator panel configuration
  - Two per loop
- Two options for fluid loop routing
  - Each have a routing to interface with the evaporator of the heat pipes

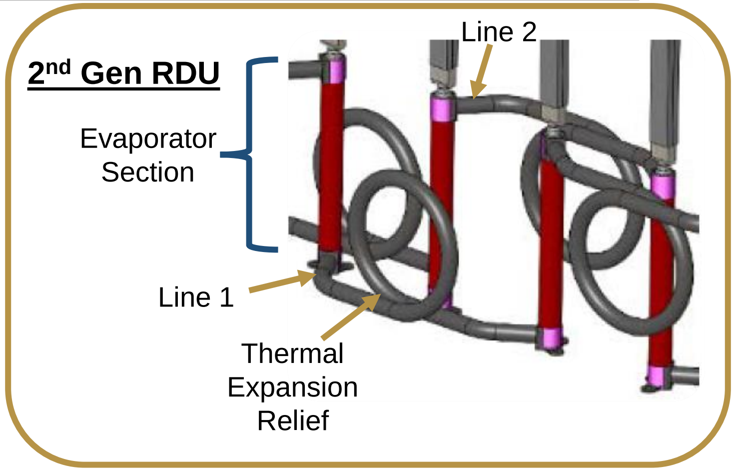


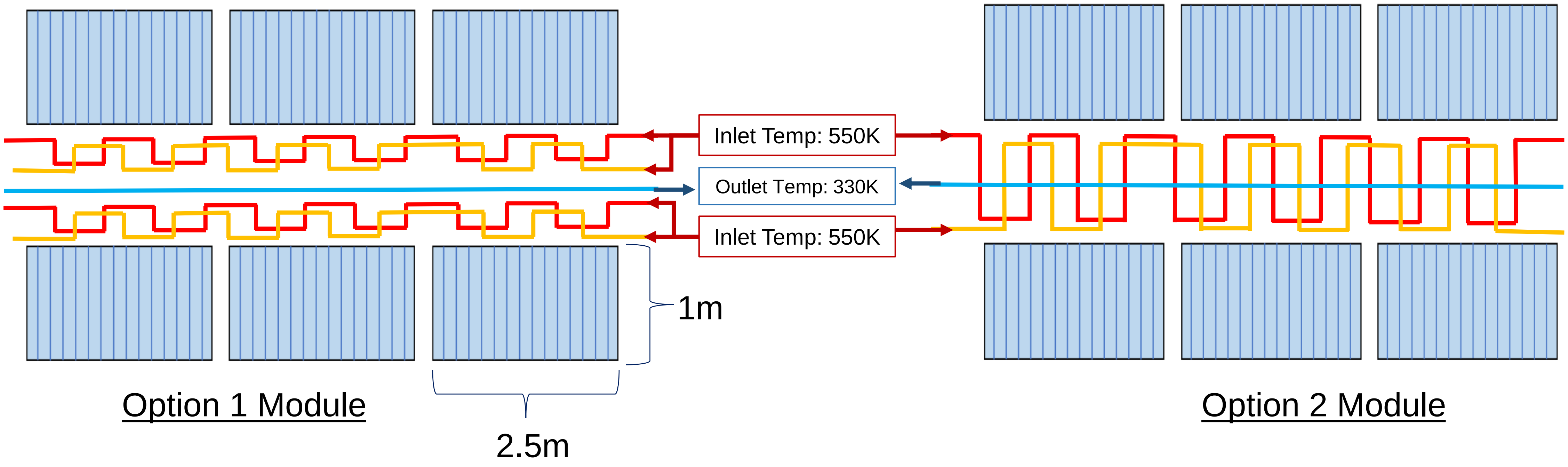




Baseline Radiator Panel Design with Fluid Loop Interface

- Using Glenn Research Center 2nd Gen Radiator Demonstration Unit (RDU) as a start
- Goal for the modular unit: inlet temp of 550K and outlet temp of 330K
- Total of 14 titanium/water heat pipes for the baseline design
  - Represented as lines on the panels below
  - Will be in-between two polymer matrix facesheets
  - Current study will identify number, diameter, and spacing
- Piping to return line at end could be removed so the fluid loop can continue to more panels
  - As the panels move away from the trunkline connection the temperature decrease for the panels
    - *Can lead to different heat pipe diameters or spacing when moving away from trunkline*
  - Location for either deployment mechanisms or iSA connection

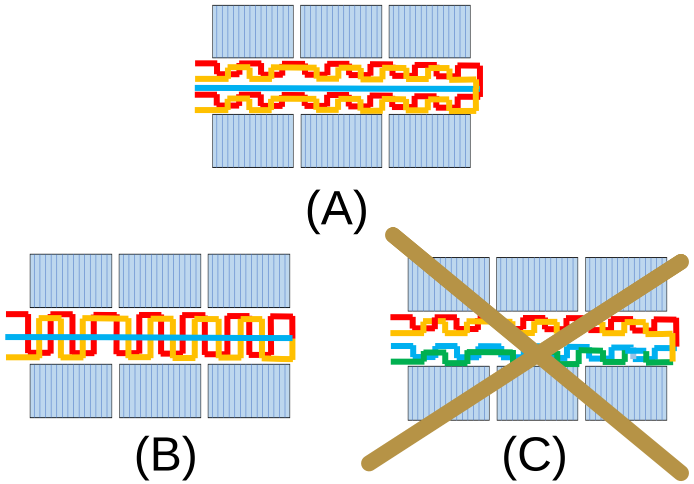


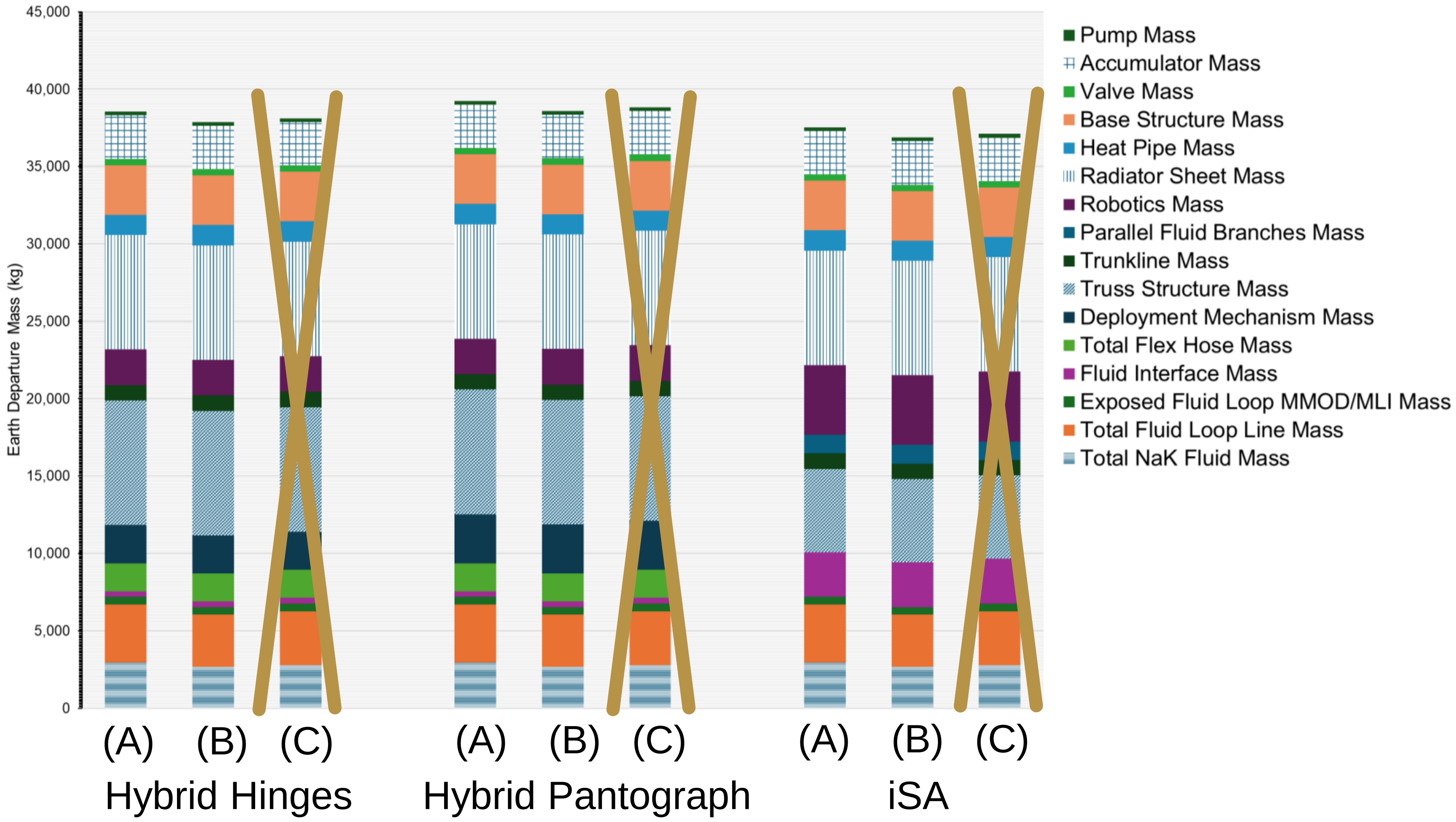


Evaporator section count does not match actual number of heat pipes

PHRS Mass Summary (TBR)

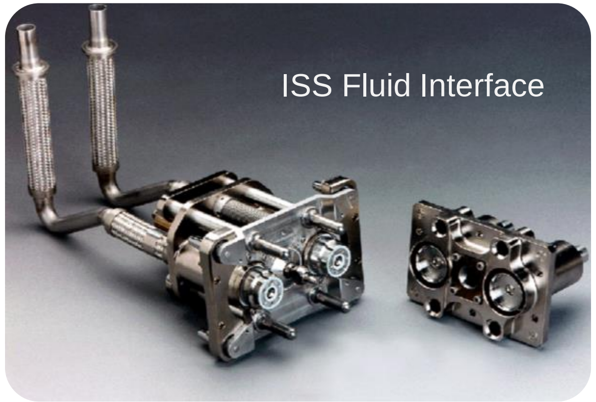
- Mass for each commissioning option were evaluated
  - Fluid loop option C was removed due to the thermal gradient between the two radiator panels in each panel set
- With uncertainty and error, the mass of the overall system is not a driver in the design



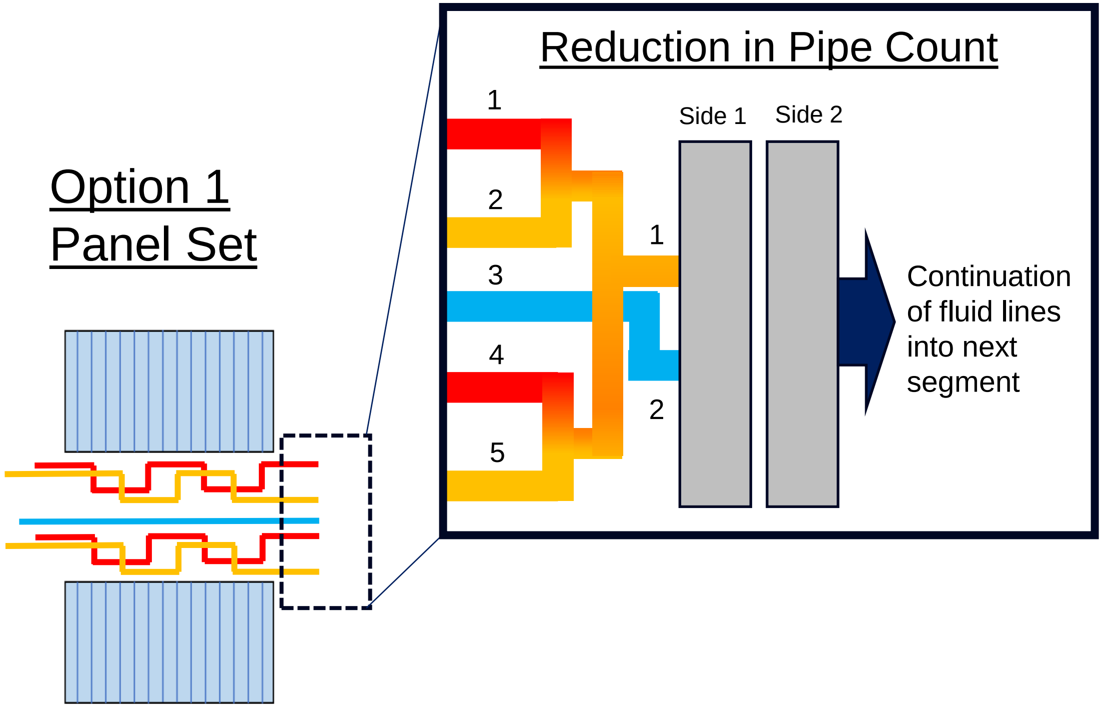


Fluid Interfaces for iSA

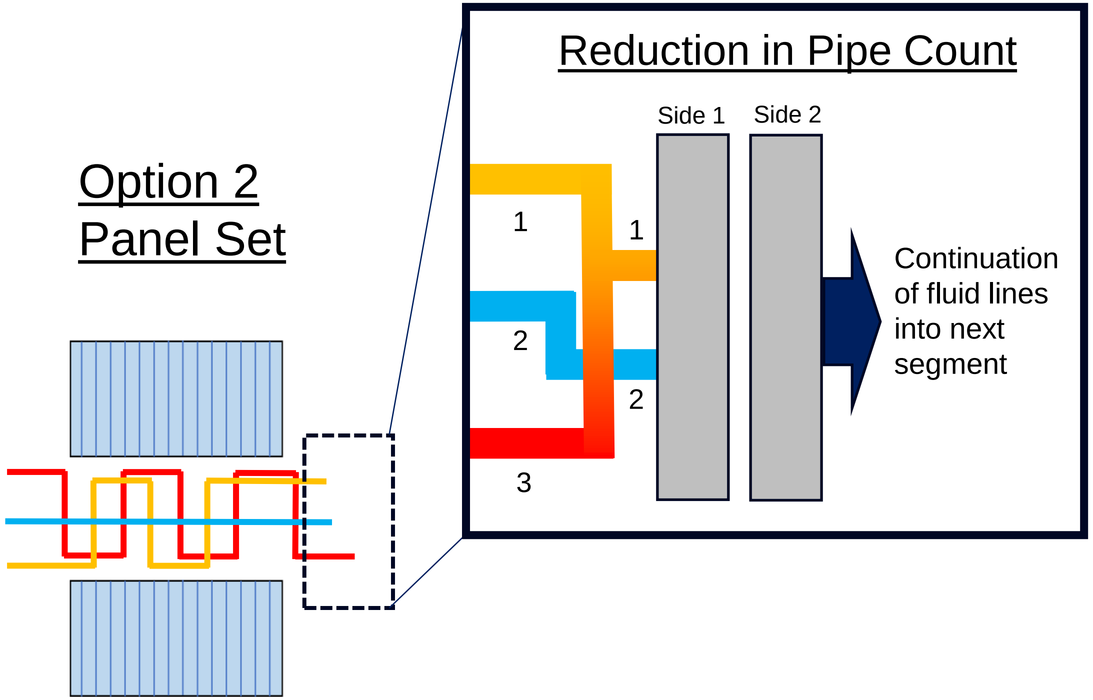
- The fluid interfaces are required for providing mechanical and fluid connection between panel sets or between an array and the truss
- Will have two parts: fluid connection and mechanical connection
  - A tight fluid connection will be made by a mechanical connection that is driven by the robotics
  - To reduce mass, it is being considered to have the motor be part of the robotics
- Mass of current design:
  - Fluid Connection: ~1.2kg (based on CAD)
  - Mechanical Locking Plate: ~3.3kg (estimate from similar systems)
  - Total: ~4.5kg
  - Number of interfaces for full iSA concept will need to consider the change in mass when compared to the hybrid concept



Option 1
Panel Set

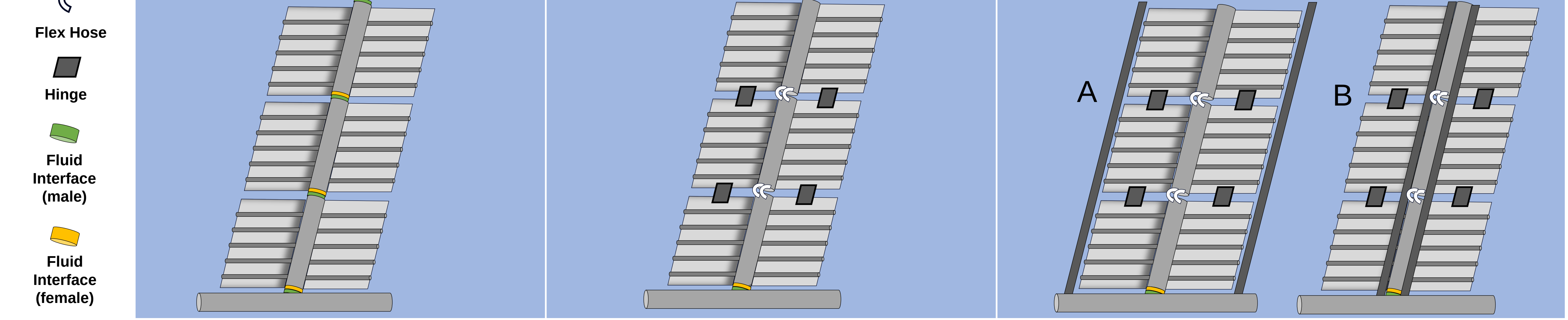


Option 2
Panel Set



*only a snapshot of pros and cons are captured below

iSA Compared with Hybrid Options



	iSA	Spring-Loaded Hinges	Scissor-Truss Mechanism
Overall route	Radiator module built up of smaller pieces using robotic arm	Variable hinge placement: center (above), panel edges, or two smaller hinges (one at edge, one inside)	A: Mechanism routed at panel edges B: Mechanism down the middle of panels, with flex hoses for some of the fluid loop sections
Pros	- Highest packaging efficiency - Smaller pieces = better ability to replace individual components if needed	- Smaller mass than scissor-truss - Mechanism failure may be isolated (location dependent)	A: Structural support of module B: - Helpful for fluid loop routing - Additional MMOD shielding for fluid loop housed in scissor truss
Cons	- Additional operational complexity - Additional commissioning time - Radiator panels *could* be cantilevered out	- Passive deployment - Less rigid - Radiator panels may be too heavy for effective mechanism function	Both heavier than spring-loaded hinges A. Heavier than spring-loaded hinges B. Radiator panels are cantilevered out; not structurally optimal

Micrometeoroid and Orbital Debris (MMOD) Analysis

- MMOD environment poses the largest threat to spacecrafts
  - Micrometeoroids: naturally occurring particles
  - Orbital Debris: man-made particles, typically satellite or spacecraft debris
- Understand environment and quantify impact threat, to inform technical items:
  - Placement constraints of critical components (eg. Fluid loop main outfeed)
  - System shielding need and corresponding system mass penalty
  - Fluid loop redundancy need
  - Potential operational recommendations during mission (eg. Inclination angle)
- Assess system protection against impact threat
- Using BUMPER-3 (NASA generated software)

Image source: NASA

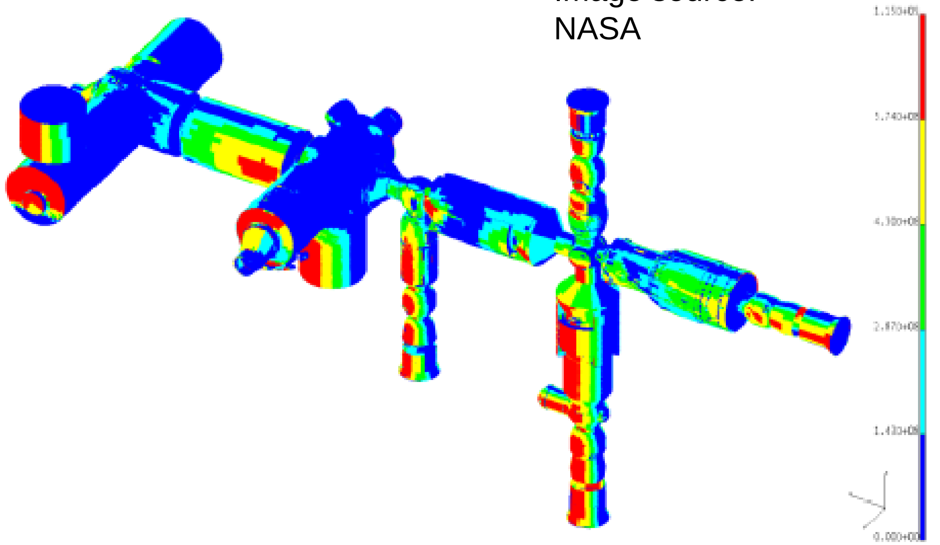
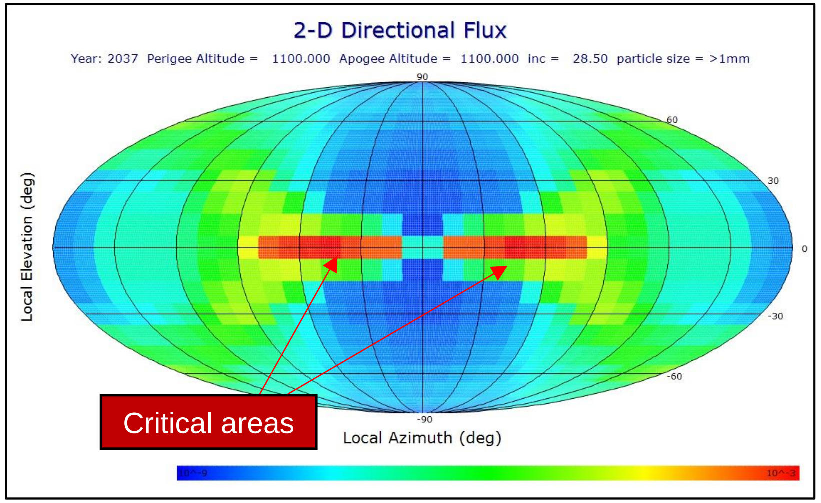


Figure 64. Contour plot of impacts per square meter for a recent ISS analysis.



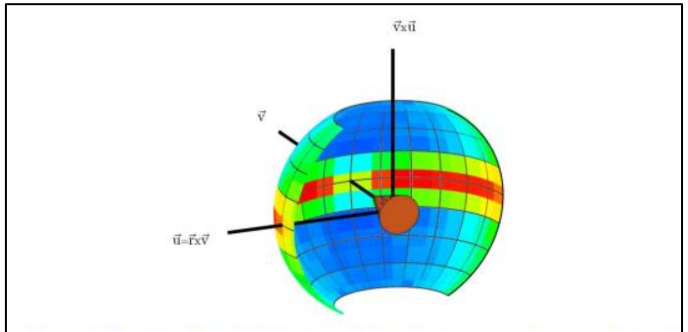
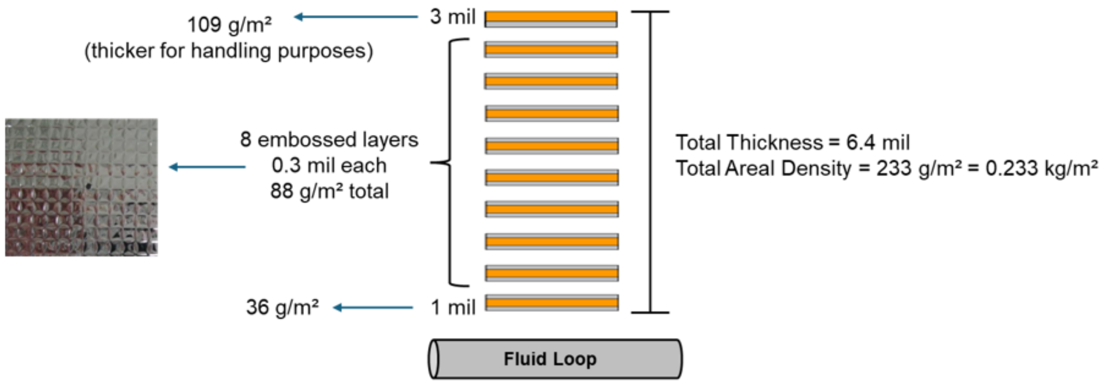


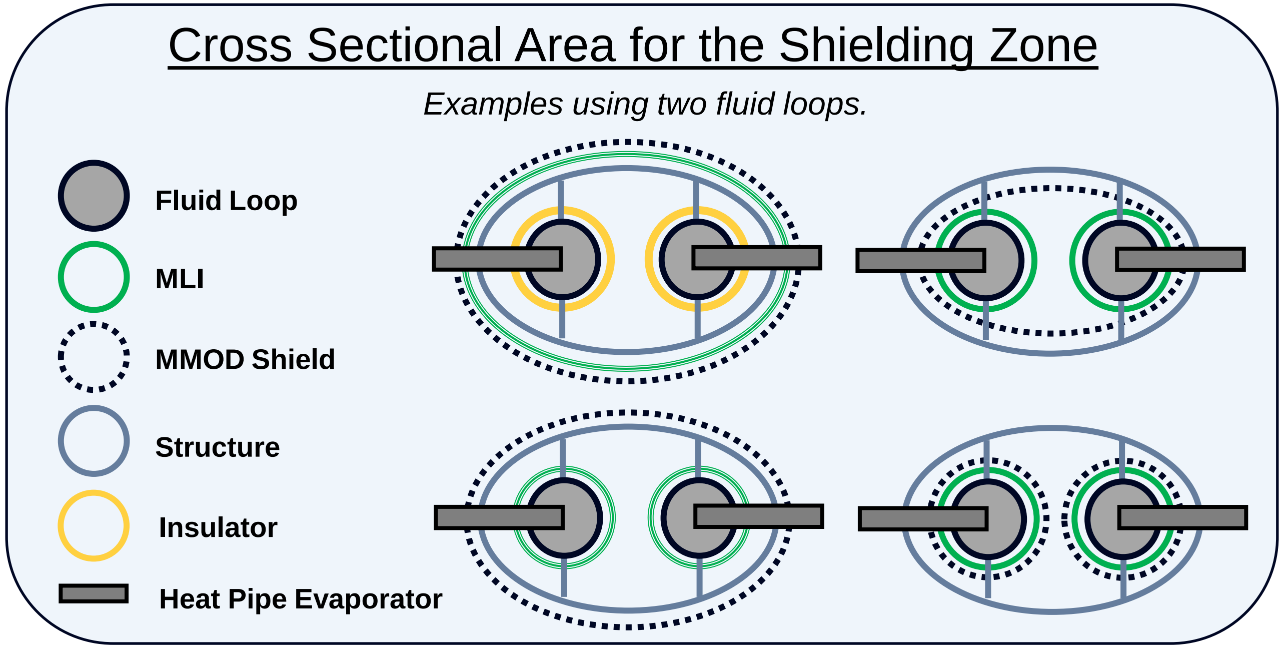
Figure 4-12 Two-dimensional directional flux projected on sphere encompassing spacecraft

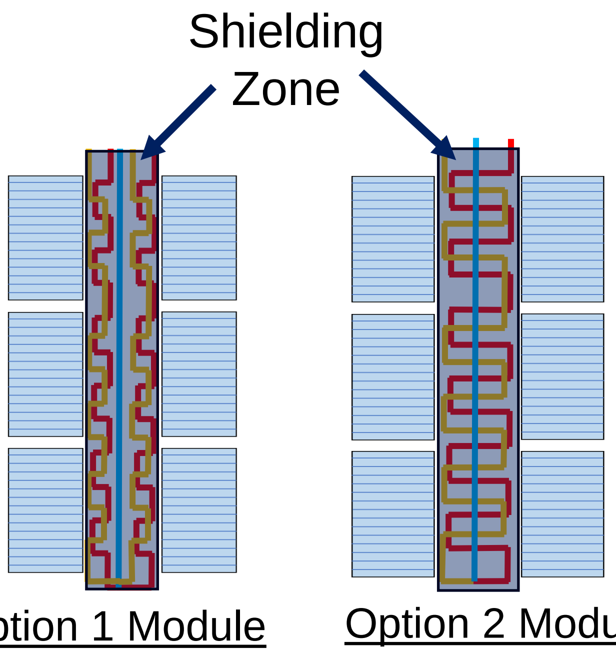
Micrometeoroid and Orbital Debris (MMOD) Analysis and MLI Shielding

- MLI is required for thermal performance
  - MMOD shielding can be integrated
  - Either needs to be wrapped around the pipes or cover the full shielding zone



MLI Layup with MMOD Considerations





System Trade Studies

Current and Past Design Trades

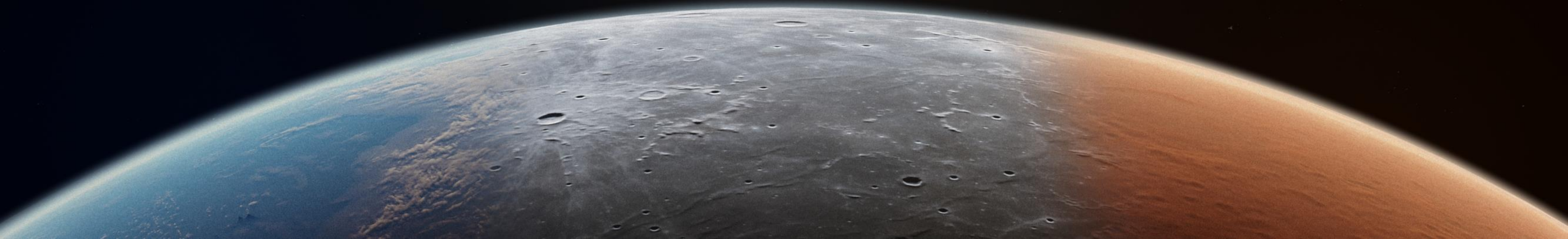
- Integrated NEP PHRS Commissioning Trade
  - Dry Mass
  - Wet Mass
- Heat Pipe Options, Spacing, and Diameter
- Pumped Thermal Working Fluid Selection
  - Water, NaK, Galinstan
- Freeze/Thaw Cycle in Fluid Loop
- Radiation Shield Mass and Geometry
- Redundancy in the MARVL SOI
- Reactor and Power Conversion Subsystem Startup
- Launch Packaging Considerations
- FMEA
- Hazards Analysis and Risks

Open Near-Term Design Trades

- Hybrid vs full assembly
- Radiator unit size (panel, module, array, wing)
- Fluid loop routing (NaK to heat pipe)
- Heat pipe discretization count

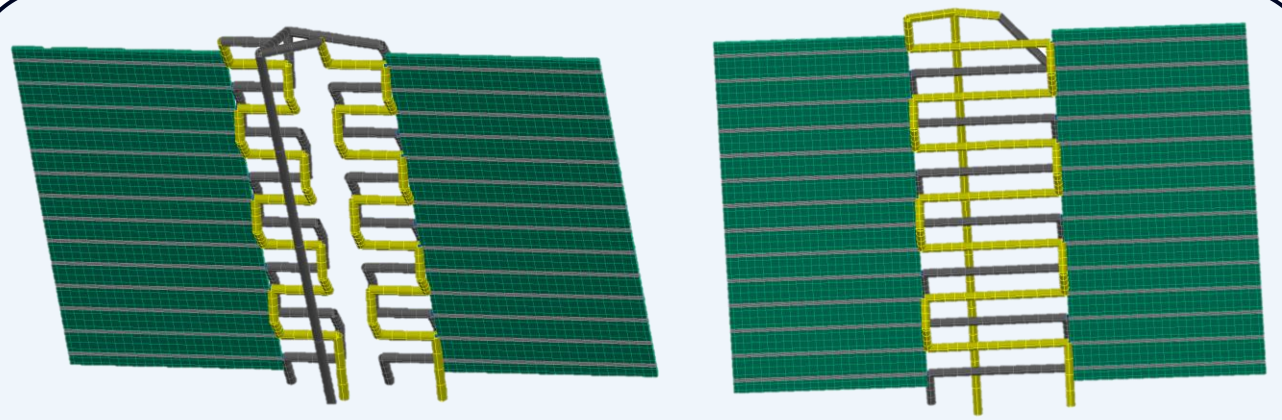
  Heat pipe diameter, spacing, temperature rating
- Hinge vs pantograph (scissor truss)
  - Flex hose design
- Fluid interface actuation (self or robotically driven)
- Fluid line coverage and support (MMOD, MLI)
- Redundancy scheme (system architecture level)

Radiator Panel and Fluid Loop



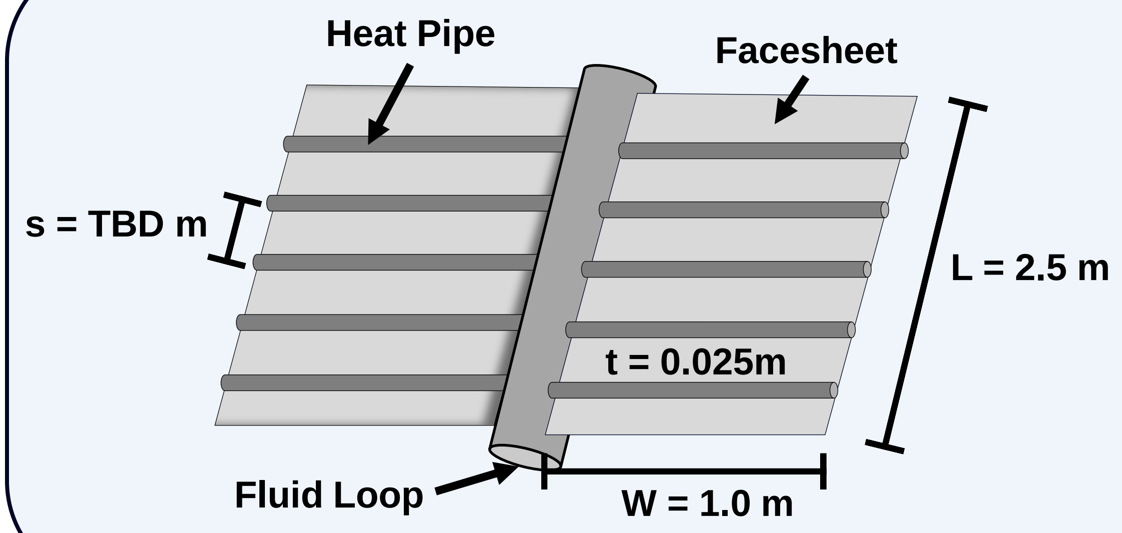
Radiator Panel Thermal Modeling

- Started with the GRC 2nd Gen RDU but with some changes
  - Difference from RDU – with the absence of gravity, heat pipes can only be 1m long for optimal efficiency
  - Radiator panels then 1m x 2.5m
  - Heat pipe specification and spacing are being worked
- A detailed Thermal Desktop model of a panel set for each option has been created
  - Recently refined so that a larger module and array can be built
- Each panel concept has been evaluated at the maximum and minimum space temperatures as identified by the mission analysis
  - 6.2K minimum sink temperature
  - 290K maximum sink temperature
- MLI or MMOD shielding should be used on the trunkline to minimize hotspots or temperature fluctuations due to orbits
  - Also maximizes radiator efficiency



Concept 1 Panel Set

Concept 2 Panel Set

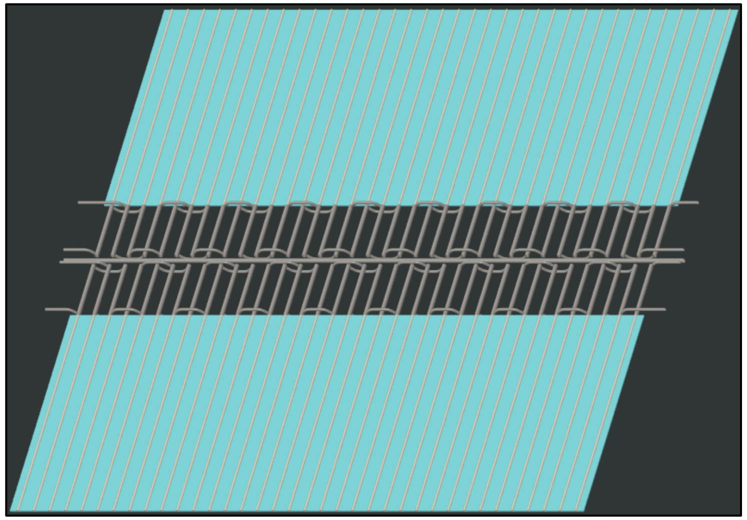


Panel Set

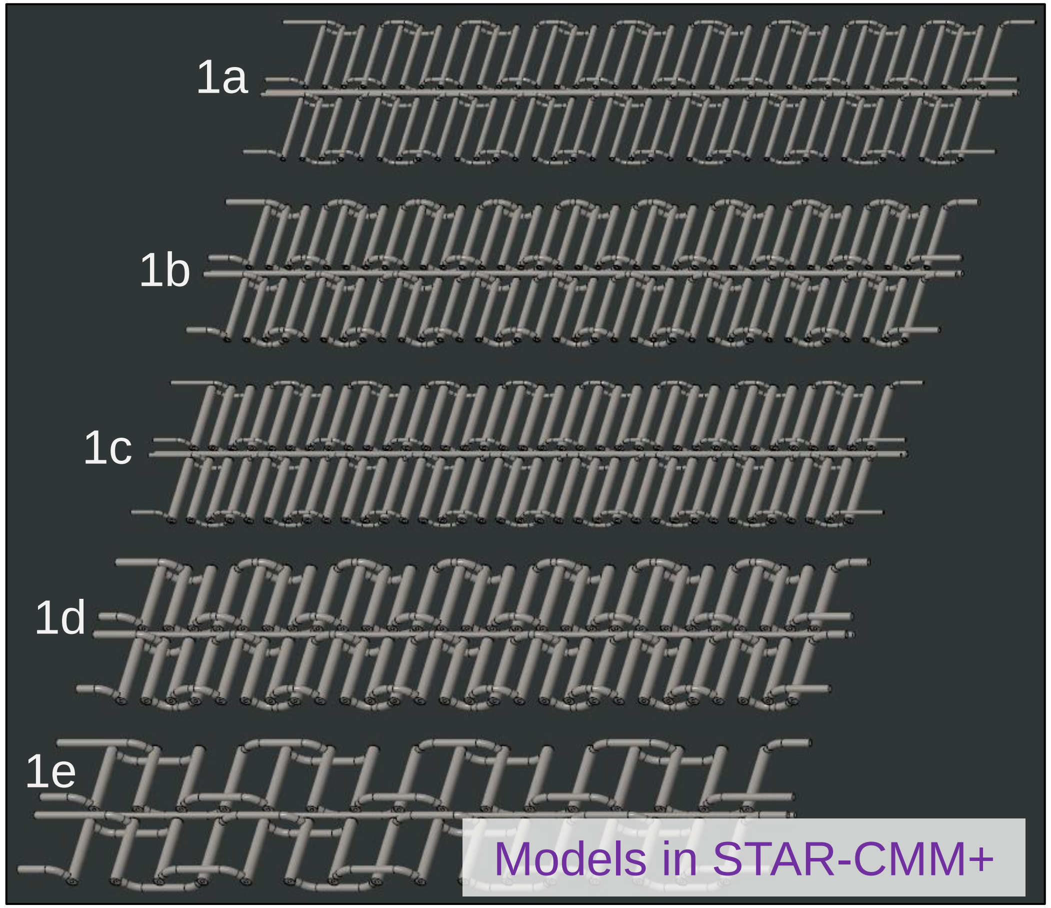
Fluid Line Mass and Volume

- Made parametric and can adjust the following:
  - Tube sizes for annular portion and inter-annular portions separately
  - Length of evaporator (annular) portion
  - Heat pipe diameter (adjustable but kept fixed for now)
  - Number of heat pipes and spacing
  - Panel-to-panel gap (adjustable but kept fixed for now)

- Various Option 1 geometries shown to the right
  - Heat pipe spacing is varied based on sets of 4 loop lines fitting within a 2.5m length



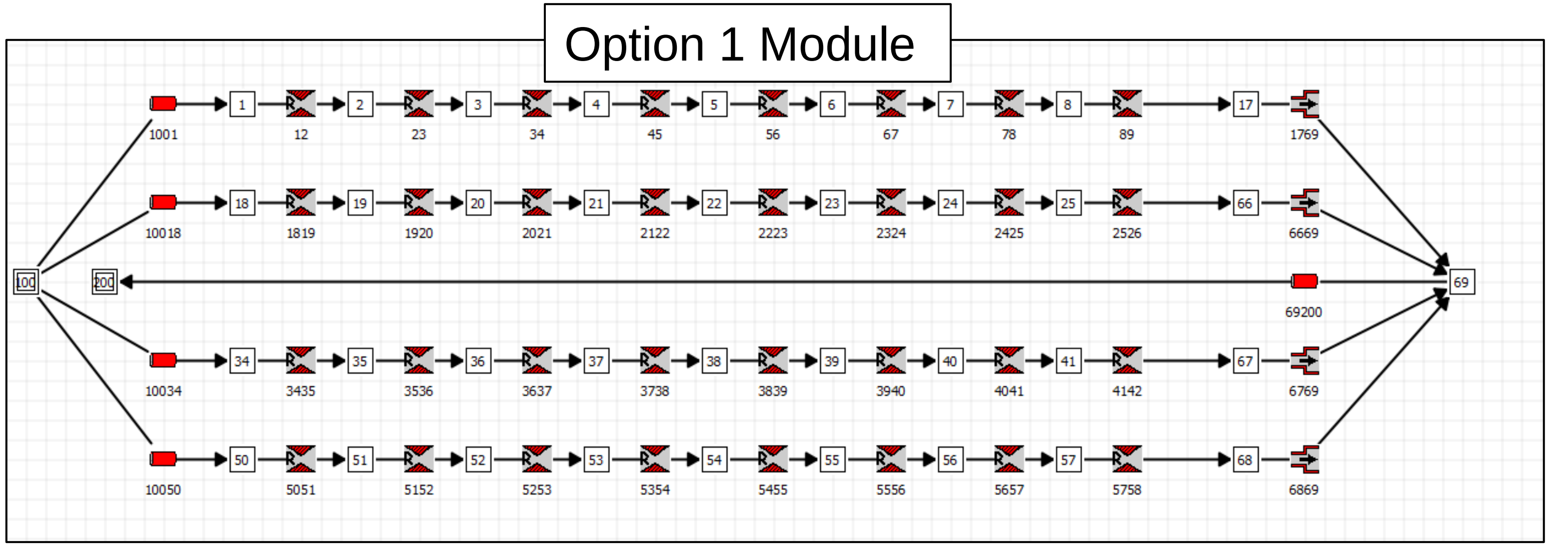
Option 1 Panel Set



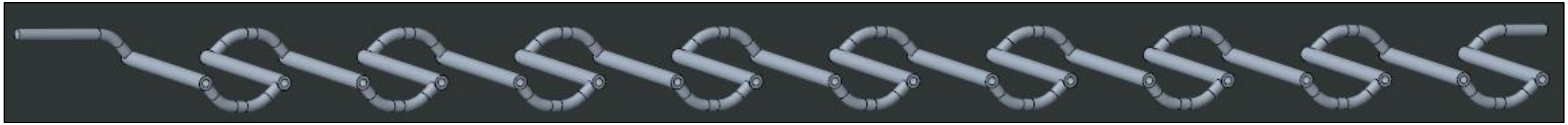
Name	# of HPs	HP spacing (in)	HP spacing (mm)	Annular Tube (in)	Inter-Annular Tube (in)	Return Tube (in)
1a	36	2.734	69.4	0.75	0.50	0.75
1b	36	2.734	69.4	1.00	0.75	0.75
1c	36	2.734	69.4	1.25	0.50	0.75
1d	28	3.515	89.3	1.50	1.00	0.75
1e	16	6.152	156.3	1.50	1.00	0.75

Pressure Drop Across Panel and Array

- Pressure drop across **radiator panel** uses internal volume for a single line built in STAR-CCM+
- Pressure Drop across **array** uses a configuration of nodes and internal volume in GFSSP

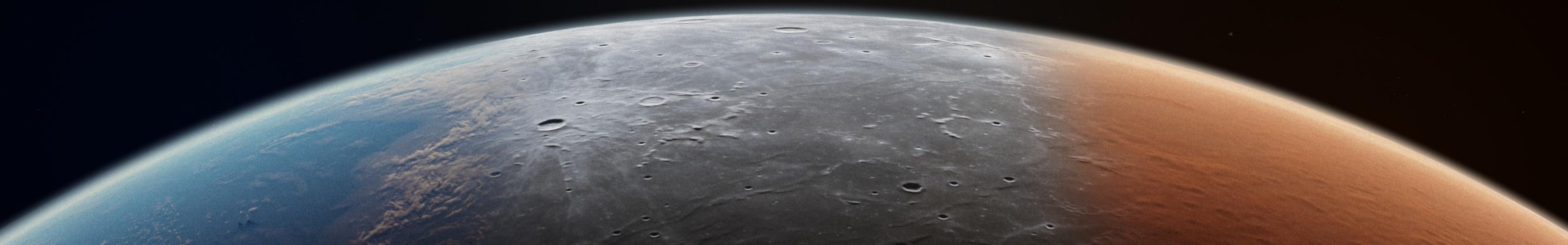


Model for predicting pressure drop across array



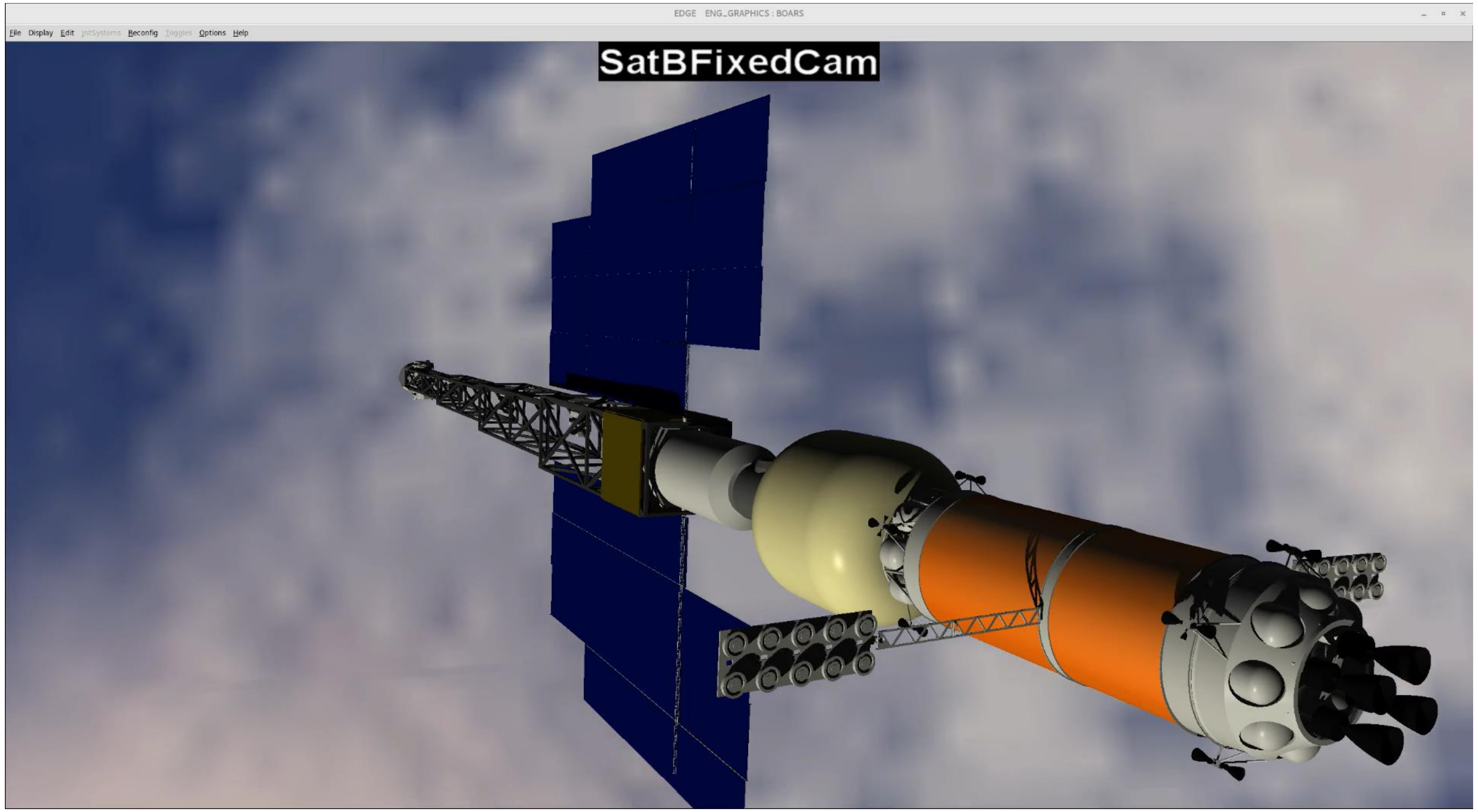
Model for predicting pressure drop across panel

Integrated Simulation



Mod/Sim Goals

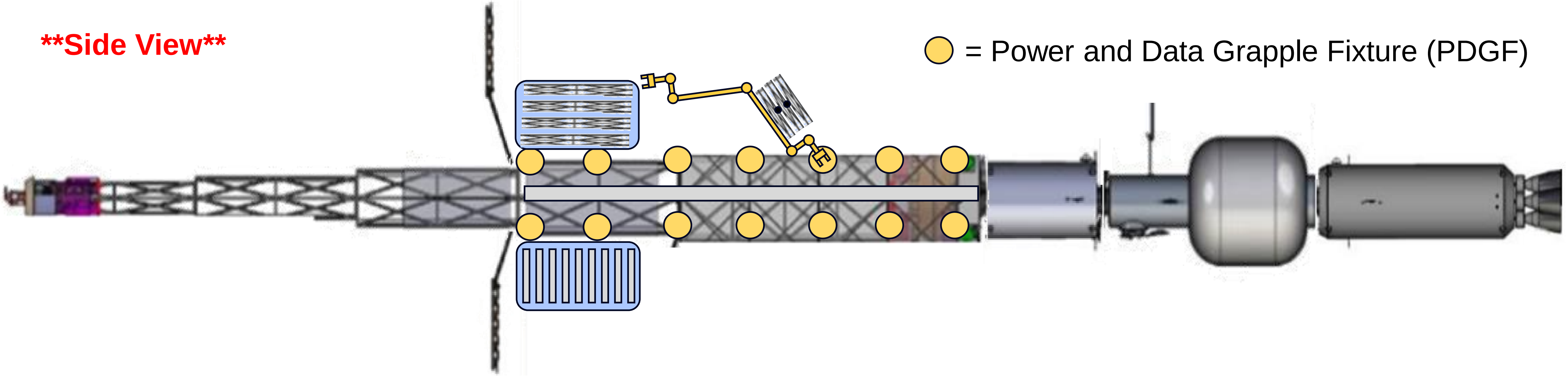
- Trade Study Requirements
- Set up shared code base
- Planning for modeling robotic operations
- Have a basic visualization of MARVL vehicle on orbit using relevant orbital physics
- Stretch Goal: Develop initial input files for the different PHRS configurations



Visualization of MARVL Vehicle On-Orbit (EDGE)

Modeling Robotic Operations

Side View



Order of Assembly Operations:

1. Robot grabs a bundle of struts from the package and attaches to its "backpack"
2. Robot moves end-over-end along the PDGFs to location of starting build point
3. Robot unpacks struts one at a time to build first row of the isogrid backbone structure
4. When there are no more struts in the "backpack", robot returns to package to get more
5. Repeat steps 1-4 until all rows of panels have been built on both wings
6. Once the isogrid backbone structure has been assembled, repeat steps 1-4 for all the radiator panels

Mod/Sim Minimum Viable Product (MVP)

- Reviewed with SNP stakeholder James Maddox

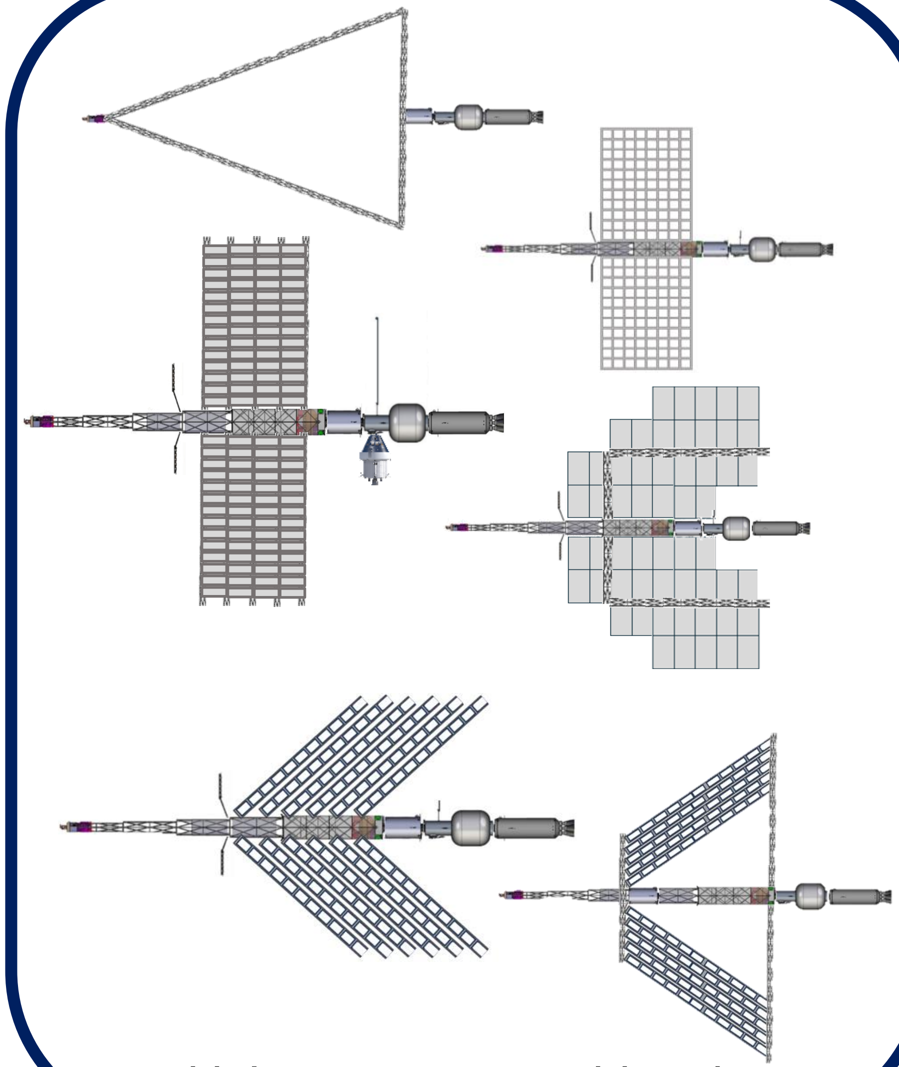
Tasks	Deliverables
Model the amount of time it will take to assemble/deploy different configurations of radiator modules. Assumptions: • Identified which manipulators to use and • Different configurations of the radiator modules have been selected • All the assembly materials have been delivered and are docked onto the trunkline/somewhere else on the vehicle	Based on the amount of time it takes for assembly/deployment for the different PHRS configurations, can determine pros/cons of the different configurations and help the team down-select configurations for further analysis. To consider: • The assembly/deployment time may impact the design of other elements of the PHRS or other parts of the overall CONOPS • Determine if there is a threshold of acceptance for the amount of time it takes for assembly/deployment
Model the different configurations of the radiator modules fully assembled/deployed and determine the attitude control requirements (fuel/DV required) for the entire vehicle in orbit, including ADCS requirements at intermediate build points.	Attitude Determination, and Control System (ADCS) requirements for the different PHRS configurations and determine if a supplemental vehicle is needed for controlling the attitude of the MTV while it's in a parking orbit. Can also identify: • How much propellant needed • Location for RCS thrusters (need to account for more piping for fuel, stresses on the system, etc.)
Conduct CONOPS testing by running trade studies on different orbits, mass properties, robotic manipulators, etc. Re-model the assembly/deployment time if the materials arrive over the course of multiple resupply launches.	
Develop visualization of assembly process using EDGE. Stretch goal: Integrate simulation in Trick with Unreal Engine.	Visualization of assembly/deployment CONOPS

Work Added to Fill Gaps and Risks

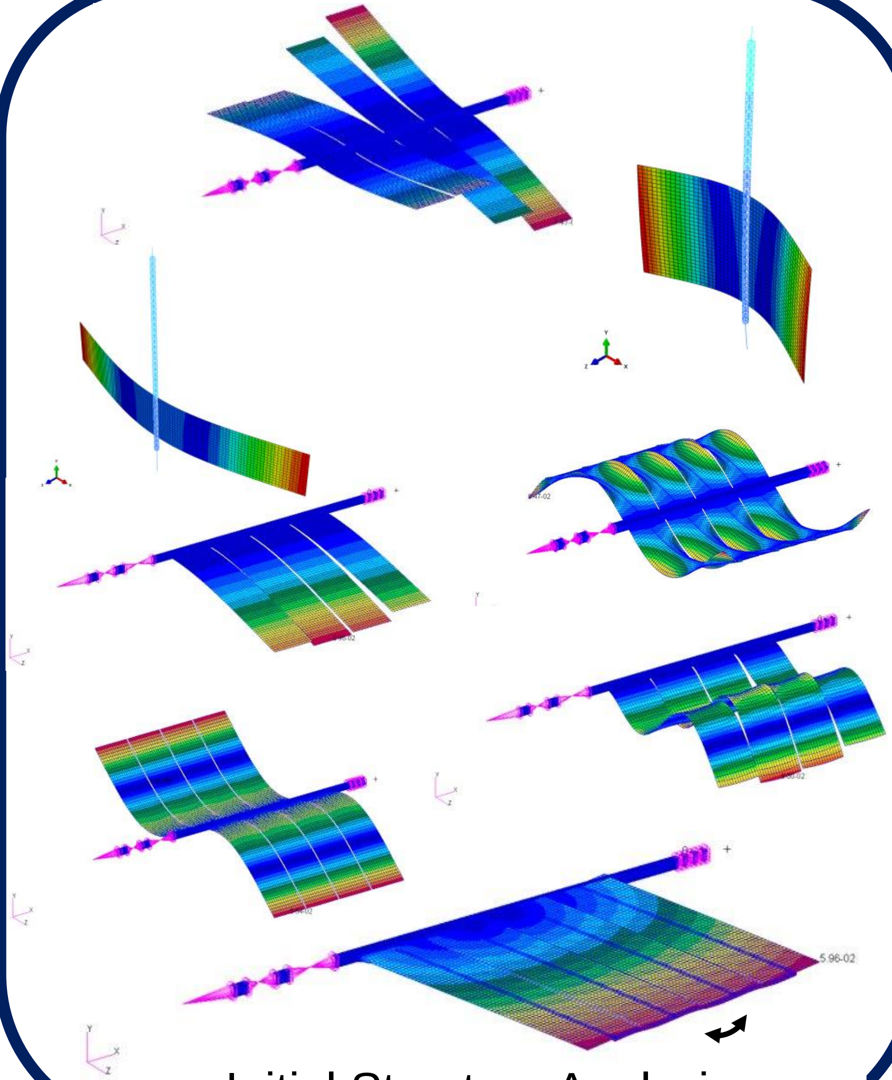
NEP Structure Study

- Looking at the NEP structure for iSA assembly support
  - Considers requirements for other NEP subsystems that rely on the NEP structure
- Comparison Metrics
  - Mass
  - Length of trunkline
  - Length of power distribution lines
  - Ease of reconfiguration
  - Qualitative metrics:
    - *Construction time (description of construction time, won't have precise values)*
    - *Assemble-ability*
    - *Radiator module scalability*
    - *Packaging needs*
    - *ACS (Attitude Control System) considerations*
  - Stiffness (frequency, redundant as we will keep constant. Mass will change)

NEP Structure Study



Initial Structure Considerations



Initial Structure Analysis

Guidance for design of the modular unit and iSA process.

Safety, Mission, Assurance

Potential Ground Hazards (subset) and Risk Assessment Codes (RAC)

- MARVL-PHRS-GND-02, Exposure of personnel to fire (RAC 3)
- MARVL-PHRS-GND-03, Exposure of personnel to explosion (RAC 3)
- MARVL-PHRS-GND-05, Exposure of sensitive electronic hardware to electrostatic discharge (RAC 3)
- MARVL-PHRS-GND-06, Exposure of personnel to sharp edges on hardware (RAC 4)

Potential In-flight Hazards (subset)

- MARVL-PHRS-FLT-02, PHRS failure in space environment due to inadequate thermal/vacuum design (RAC 3)
- MARVL-PHRS-FLT-04, Structural failure of PHRS (RAC 3)
- MARVL-PHRS-FLT-07, Damage to PHRS parts during in-space assembly (RAC 3)
- MARVL-PHRS-FLT-09, Damage of PHRS due to MMOD impact (RAC 2)
- MARVL-PHRS-FLT-10, Water and NaK Mixing (RAC 2)
- MARVL-PHRS-FLT-11, Loss of thermal control (RAC 2)

RISK ASSESSMENT MATRIX

SEVERITY / PROBABILITY	Catastrophic (I)	Critical (II)	Marginal (III)	Negligible (IV)
Frequent (A)				
Probable (B)				MARVL-PHRS-GND-06
Occasional (C)		MARVL-PHRS-FLT-09 MARVL-PHRS-FLT-10	MARVL-PHRS-GND-01 MARVL-PHRS-GND-04	MARVL-PHRS-FLT-05
Remote (D)	MARVL-PHRS-FLT-11	MARVL-PHRS-GND-02 MARVL-PHRS-GND-03 MARVL-PHRS-FLT-07 MARVL-PHRS-FLT-08	MARVL-PHRS-GND-05	MARVL-PHRS-GND-07
Improbable (E)	MARVL-PHRS-FLT-01 MARVL-PHRS-FLT-02 MARVL-PHRS-FLT-04		MARVL-PHRS-FLT-03 MARVL-PHRS-FLT-06	

RAC 1
RAC 2
RAC 3
RAC 4

- Risk Assessment Matrix, meets the intent of MIL-STD-882E, Standard for System Safety and NF1825
- Scoring reflects verified mitigations in place

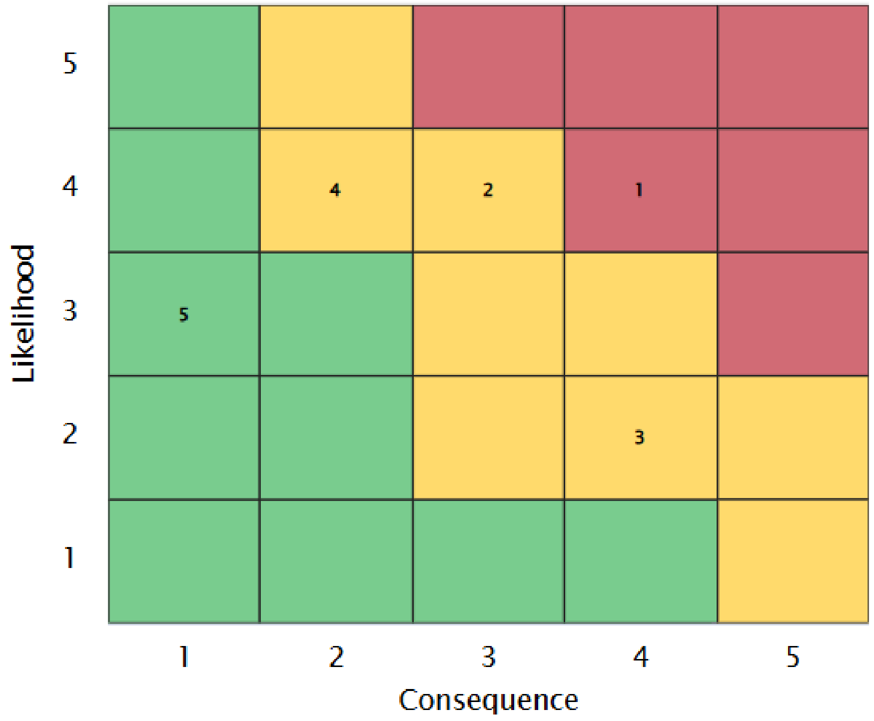
Risks

- Risks are updated after each DAC Sync
  - Last update was after the Focus Peer Review
- Using RiskMAP to stay organized
- Most risks are at a watch or research stage since we are not working with hardware (yet)

	Rank	Trend	LxC	RS	Category	Approach	ID	Title
🗋	1	→	4 x 4	22	Te	Re	010	Material Compatibility (NaK and Titanium)
🗋	2	☐	4 x 3	18	Te	Mi	007	Technology Development hindrance due to gaps in Mars transit vehicle design
🗋	3	☐	2 x 4	14	Te	Wa	011	NaK Freeze/Thaw Cycle in Fluid Lines (Solid Packing)
🗋	4	☐	4 x 2	13	Te	Wa	013	Contamination Due to NaK Leakage During Disconnect
🗋	5	☐	3 x 1	4	Te	Wa	012	Liquid NaK Thermal Expansion

Te: Technical | Re: Research | Mi: Mitigate | Wa: Watch

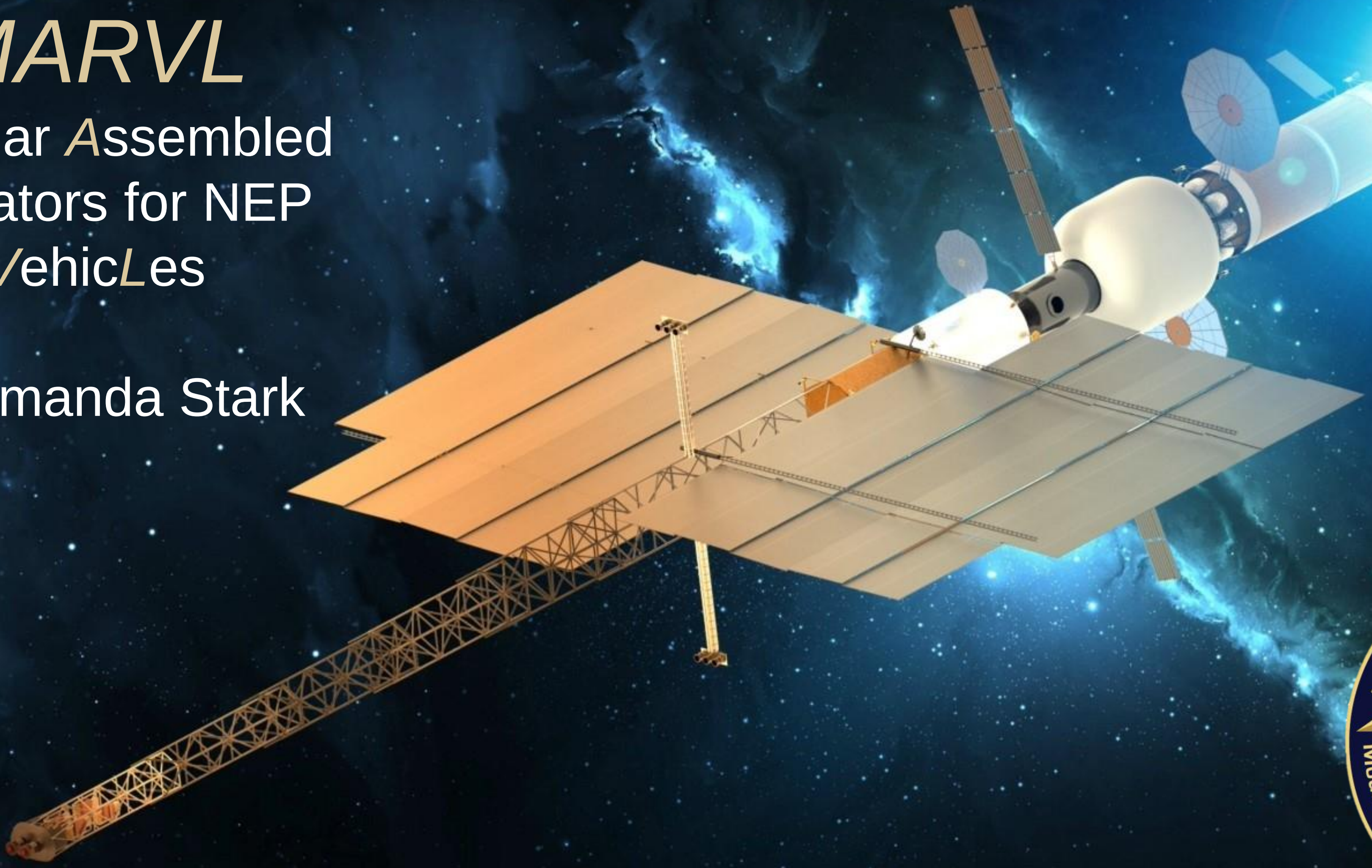
☐ New | ↑ Worsening | ↓ Improving | → No Change



MARVL

*M*odular *A*ssembled *R*adiators for NEP *V*ehic*L*es

PI: Amanda Stark



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