Modular Assembled Radiators for Nuclear Electric Propulsion (NEP) VehicLes (MARVL) Project Thermal Technology Development

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Overview

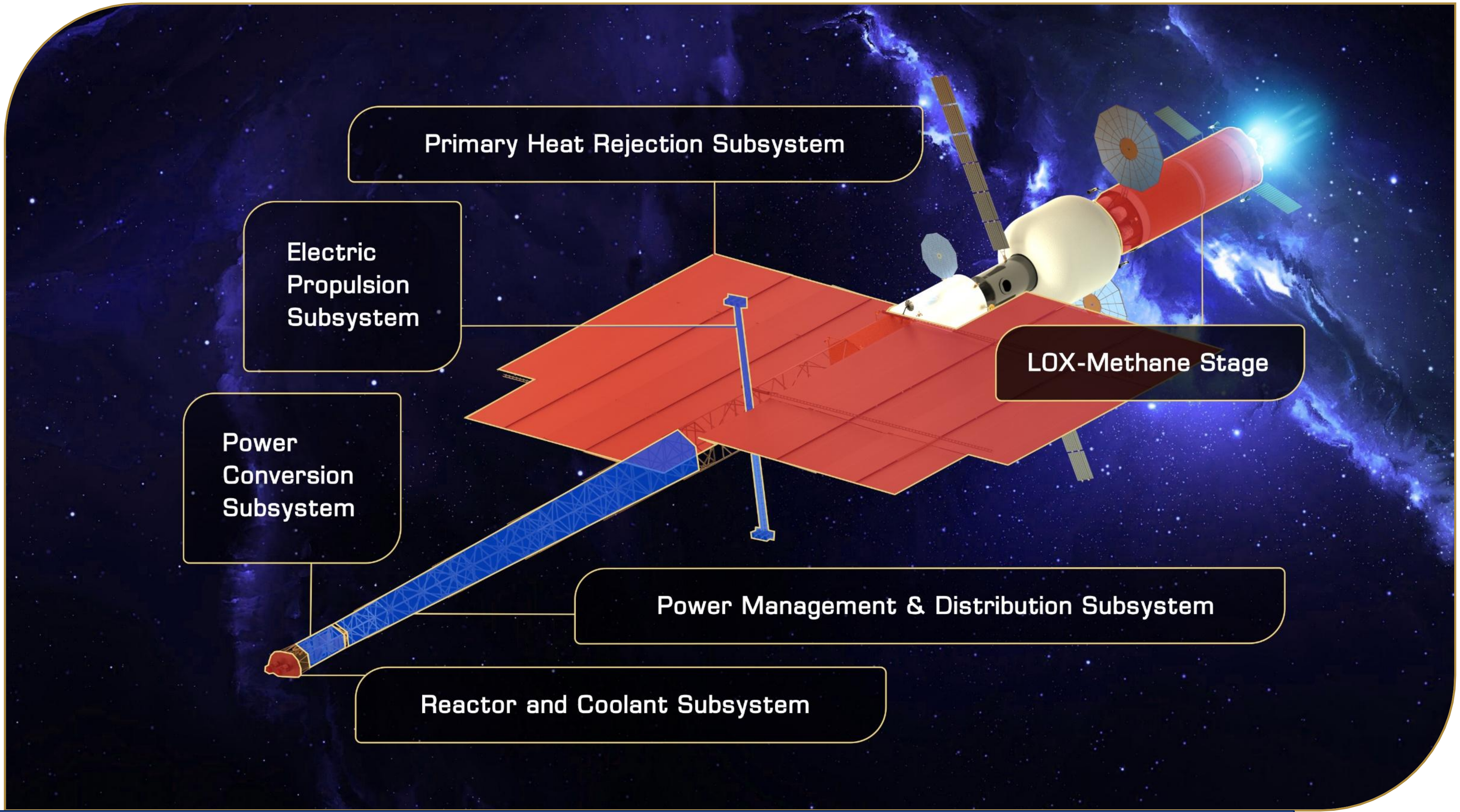
- Nuclear Electric Propulsion (NEP) Introduction
- Modular Assembled Radiators for NEP VehicLes (MARVL) Background
- NEP Power Requirements and Waste Heat
- Subdivision for Radiator Surface Area
  - First Year Process
  - Technical Developments
- Conclusion

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.

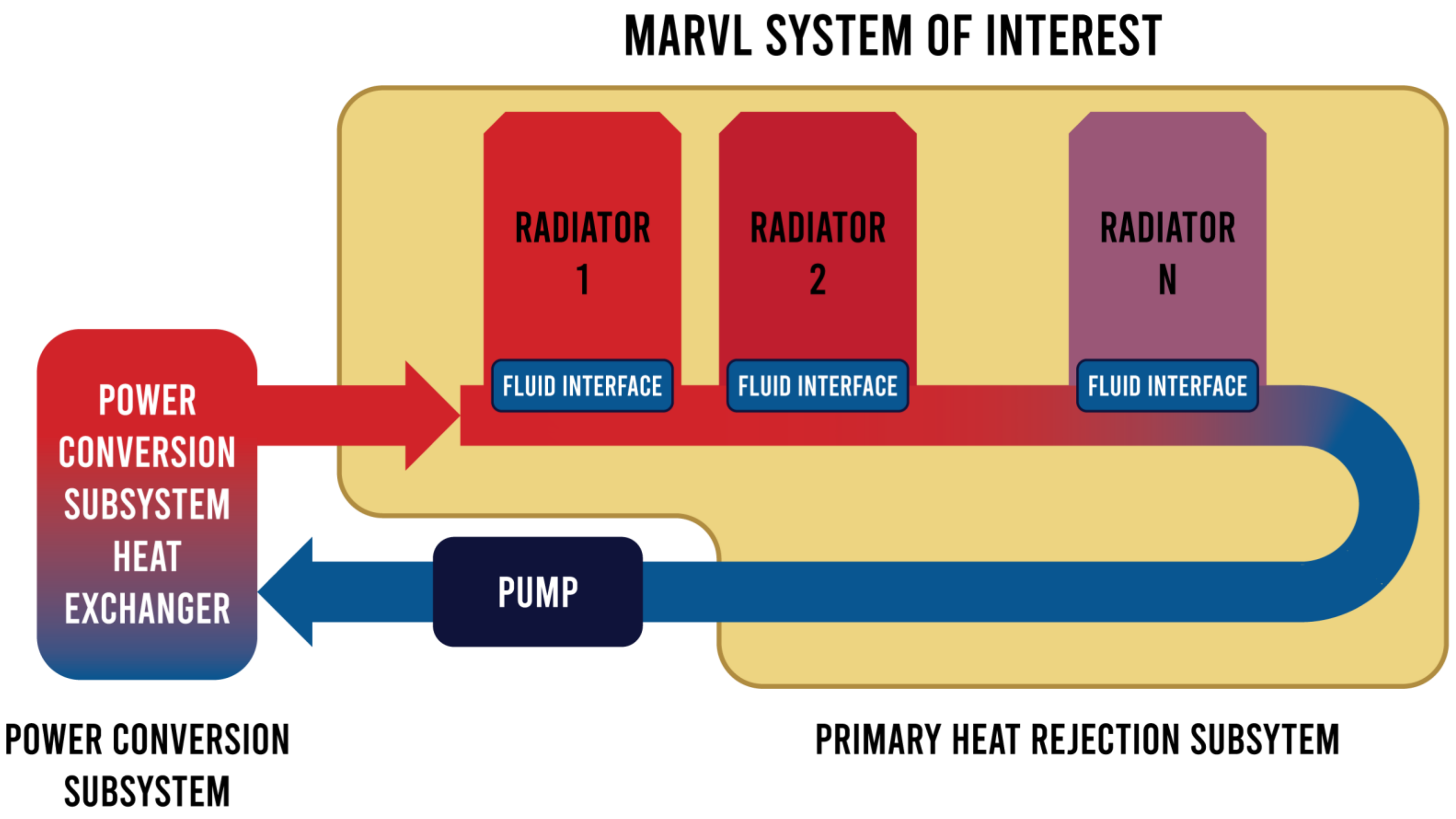
Note: The NEP System of Spacecraft shown is an artist's rendition of the crewed version with one EPS propellant stage. The vehicle configuration and number of elements changes throughout the Mars Opposition Class mission. One possible set of subsystem placements is shown and is subject to change.

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

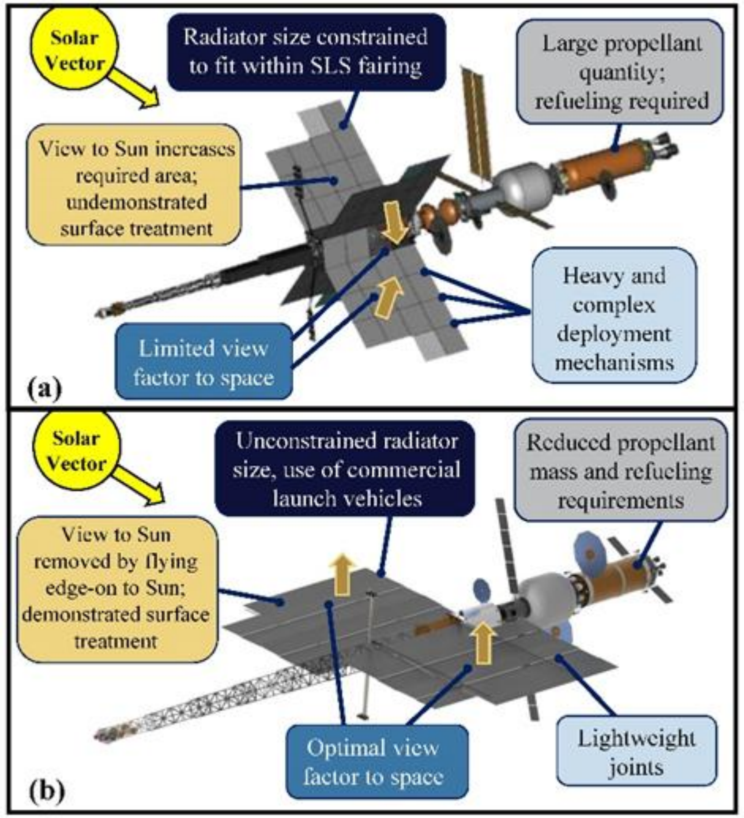


Incorporating in-Space Assembly

Flight orientation results in view factor losses which increases mass

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

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



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

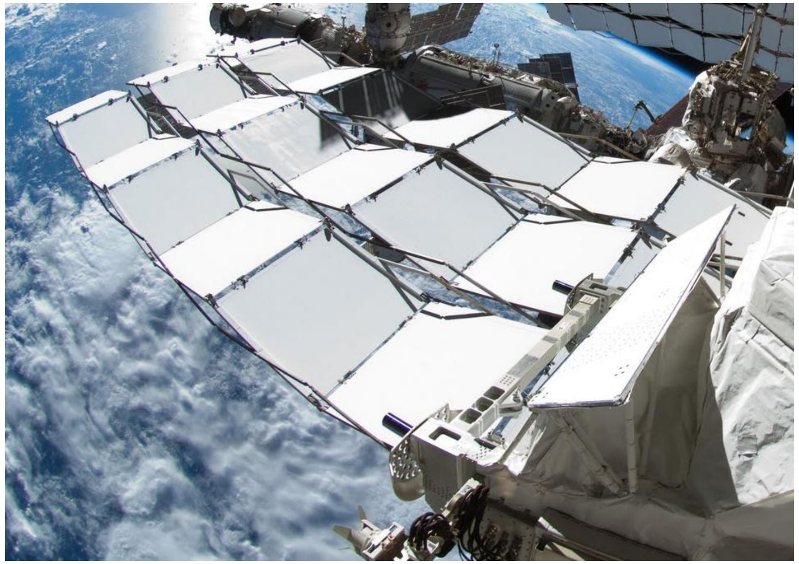
- Use of in-Space Assembly (iSA) in designing NEP modular radiators has the potential to improve overall vehicle performance while reducing mass, schedule, cost, and risk.
- Enables (1) mass-efficient bi-wing design, (2) architectural flexibility, and (3) use of commercial launch vehicles

State of the Art - ISS Radiators

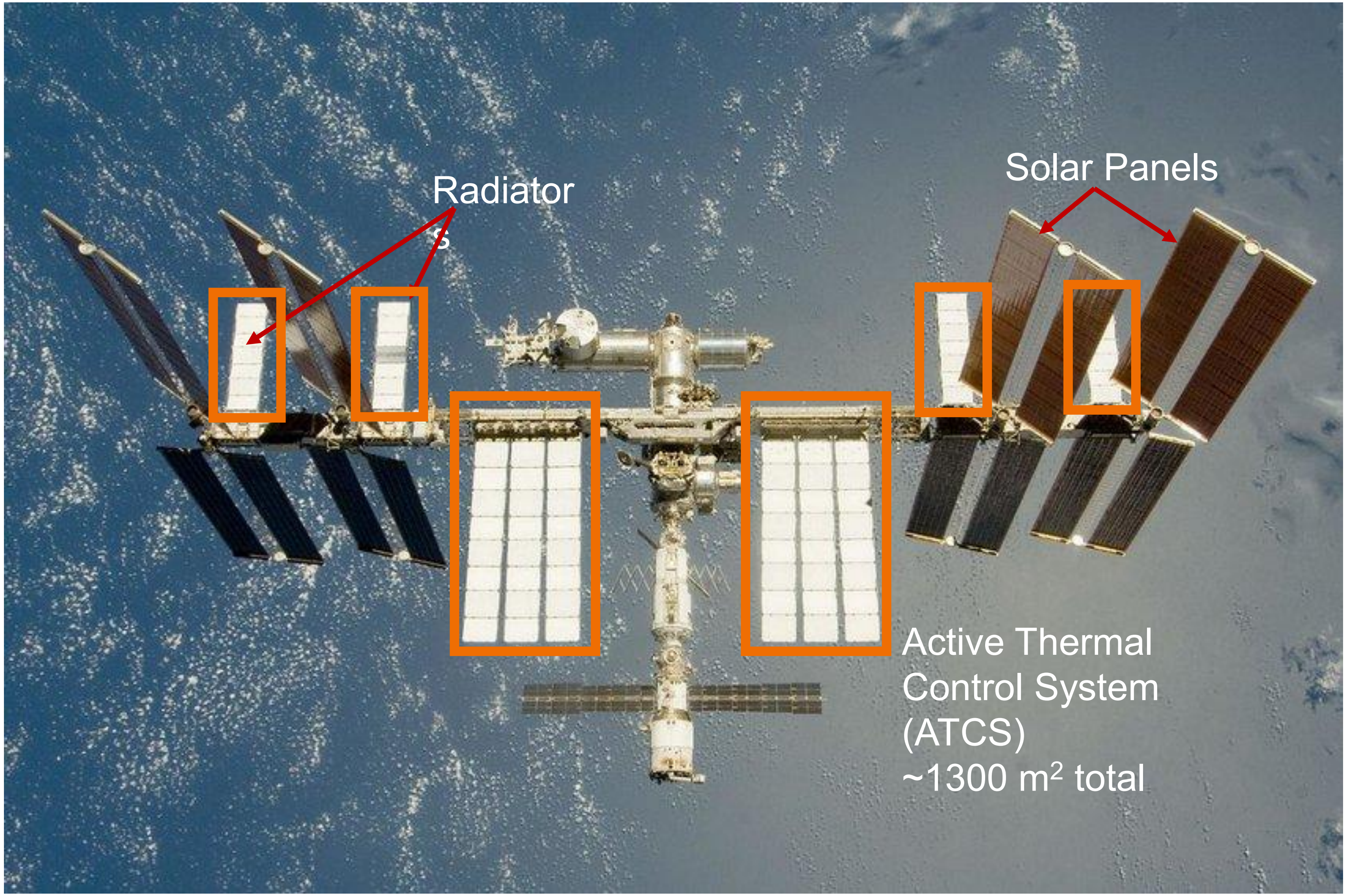
- The International Space Station (ISS) Active Thermal Control System (ATCS) radiator arrays, with their Orbital Replacement Unit (ORU) interfaces, are the most relevant state of the art in terms of size and commissioning approach
  - ISS radiator arrays were launched in several segments, robotically 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



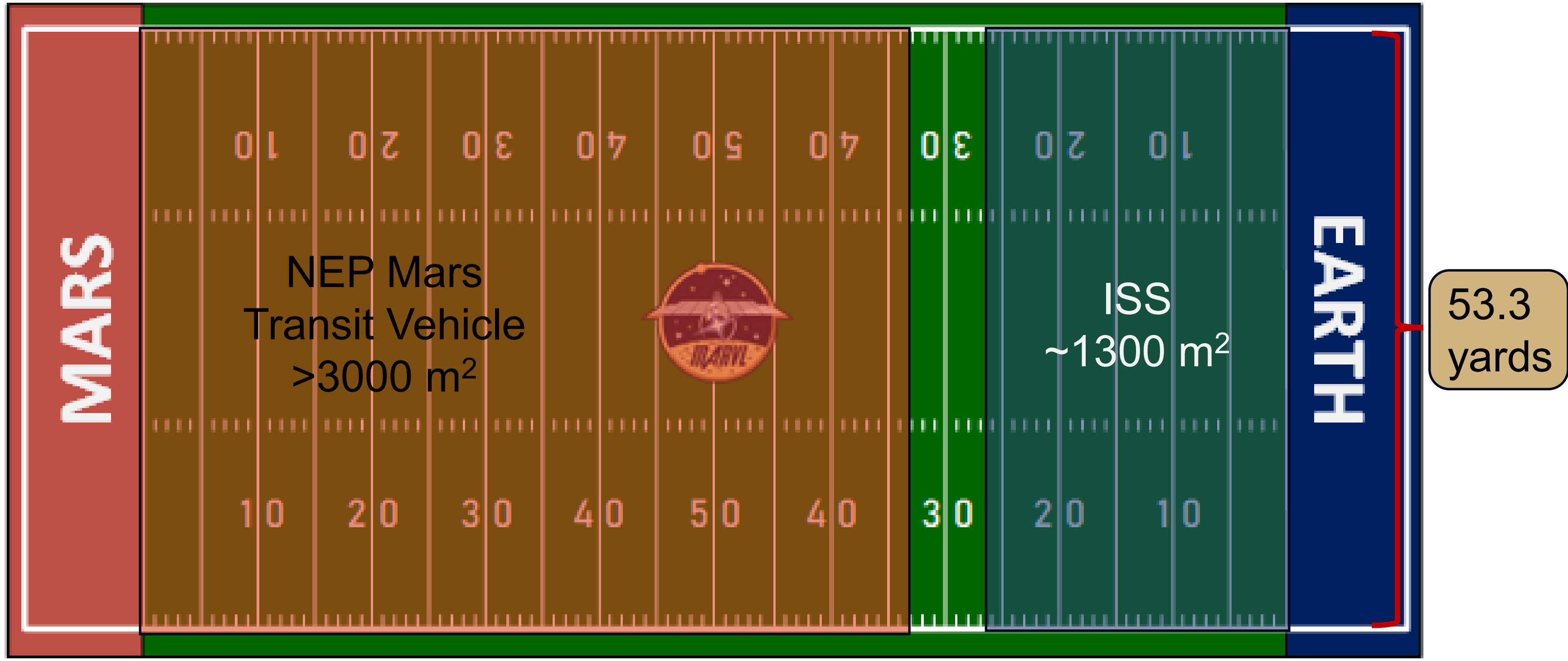
State of the Art



NEP Vehicle vs. International Space Station for Radiator Area

ISS Total Radiator Area: ~1300 m^2 (13993.08 ft^2)

NEP Mars Vehicle Total Radiator Area: >3000 m^2 (32291.73 ft^2)



Space radiators are usually double sided.
So, the area presented here is total area needed.
In actuality, the radiators will only be half this size.

Modular Assembled Radiator for NEP VehicLes (MARVL) Background

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)

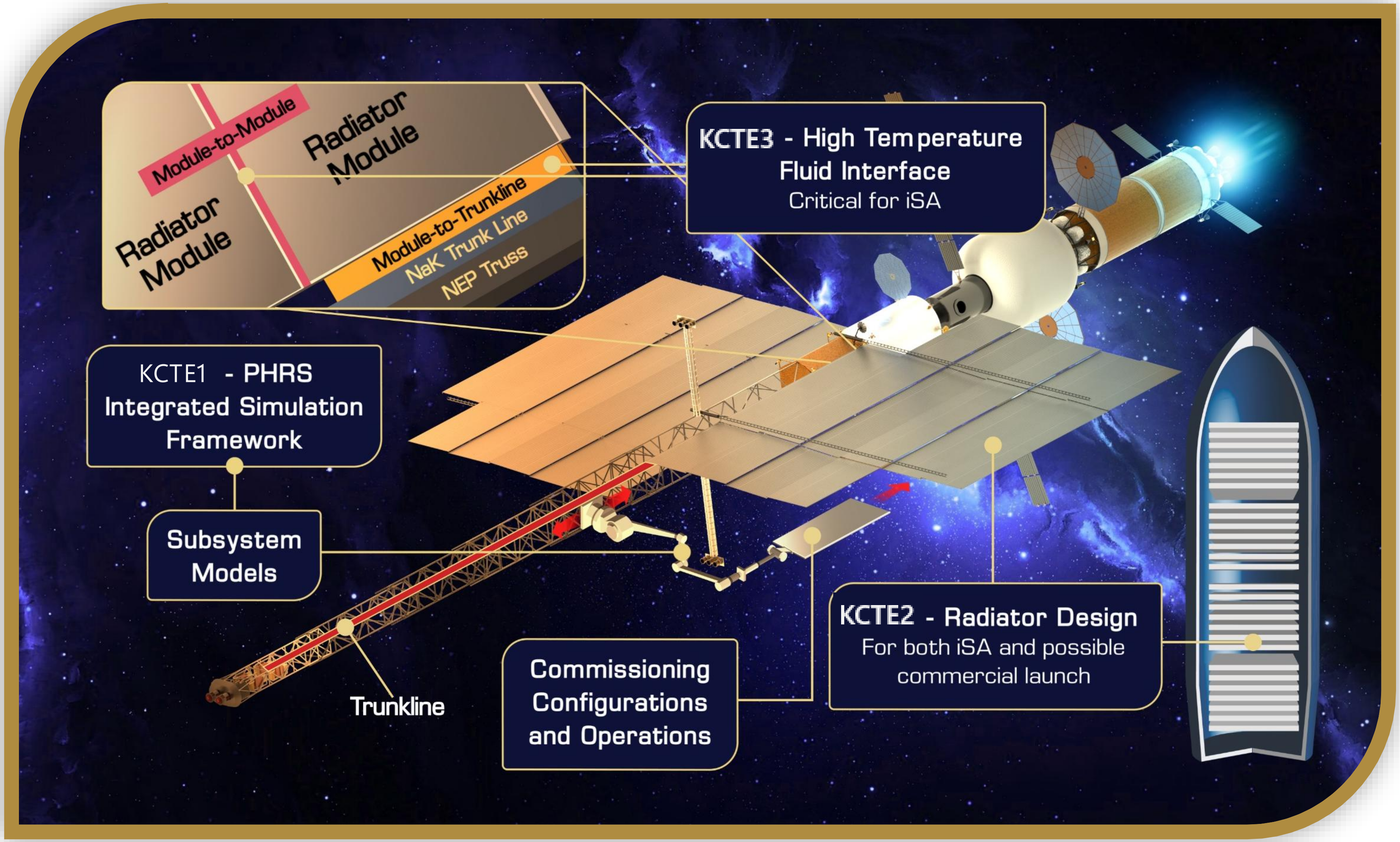
Title	Description	Unit	SoA	Threshold	Goal
PHRS specific mass (α)	PHRS mass per unit electrical power produced by nuclear reactor	kg/kWe	~11*	8†	3.5‡

*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 Key Critical Technical Elements

Key Critical Technical Elements (KCTE):

- KCTE1 – PHRS Integrated Simulation Framework
- KCTE2 – Radiator Design
- KCTE3 – High Temperature Fluid Interface

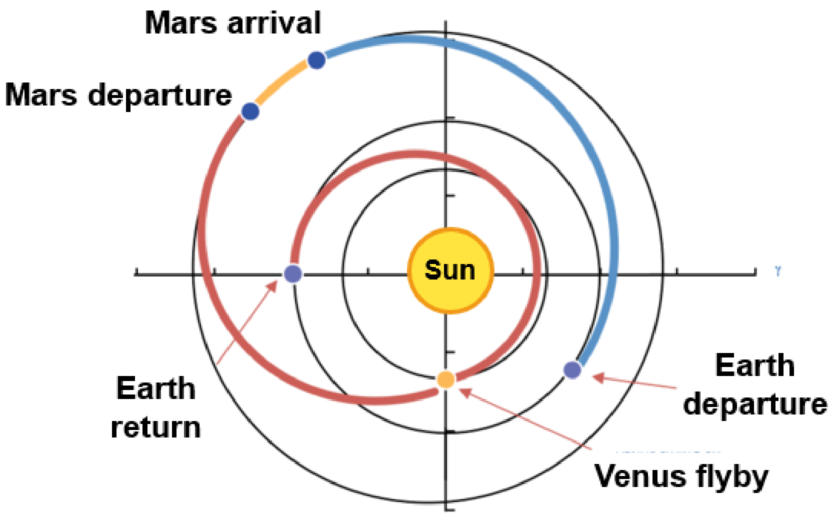


Enveloping Mars Mission – Environmental Modeling

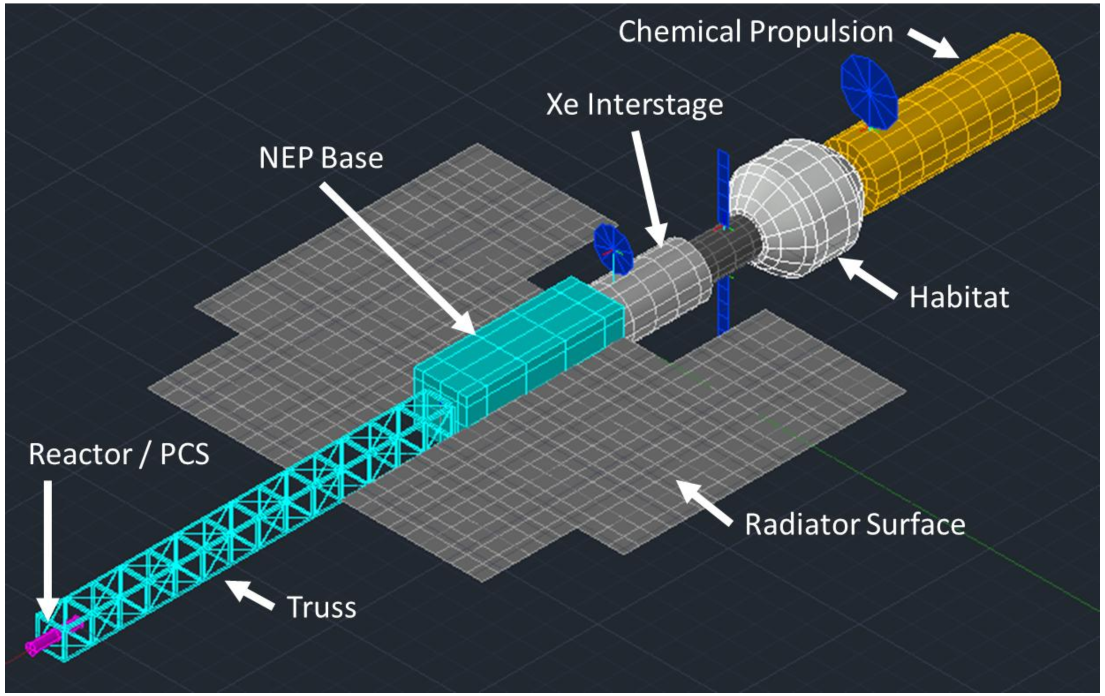
- The target application for technology development is a Crewed NEP Mars Opposition Class Mission:
  - Crew departure date: 2039
  - Total mission duration: ~3 years
  - Hybrid NEP/chemical vehicle (NEP for cruise phases & chemical stage to enter/exit gravity wells)

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



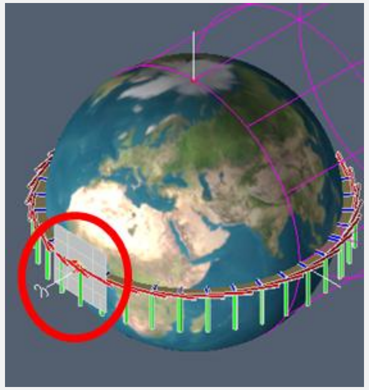
Thermal Desktop Model for the NEP Vehicles

Thermal Worst Cases Utilizing a Plate Model

- **Total number of cases from 328 reduced to 4 hot and cold extrema cases**
  - Study used a radiative surface at key mission locations to determine sink temperature extremes
  - Reactor power was ON and OFF
  - The simple plate model is a good approximation (+/- 8% heat rejection capability) and radiator properties can be varied parametrically

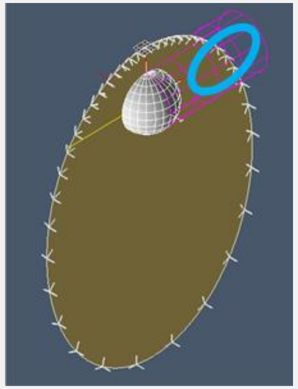
Reactor powered OFF

Max
Plate = 353 K



LEO, 500 km altitude
0° beta angle
Face to Earth, Edge to VV
Position: subsolar point

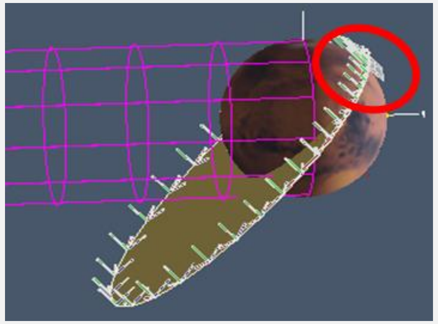
Min
Plate = 30 K



NRHO
0° beta angle
Face to Sun
Position: within shadow

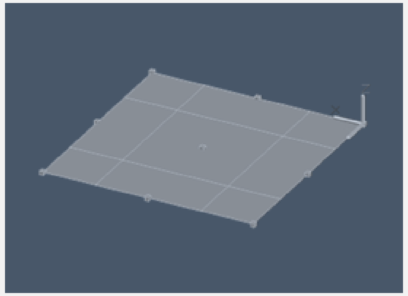
Reactor powered ON

Max
Plate = 243 K



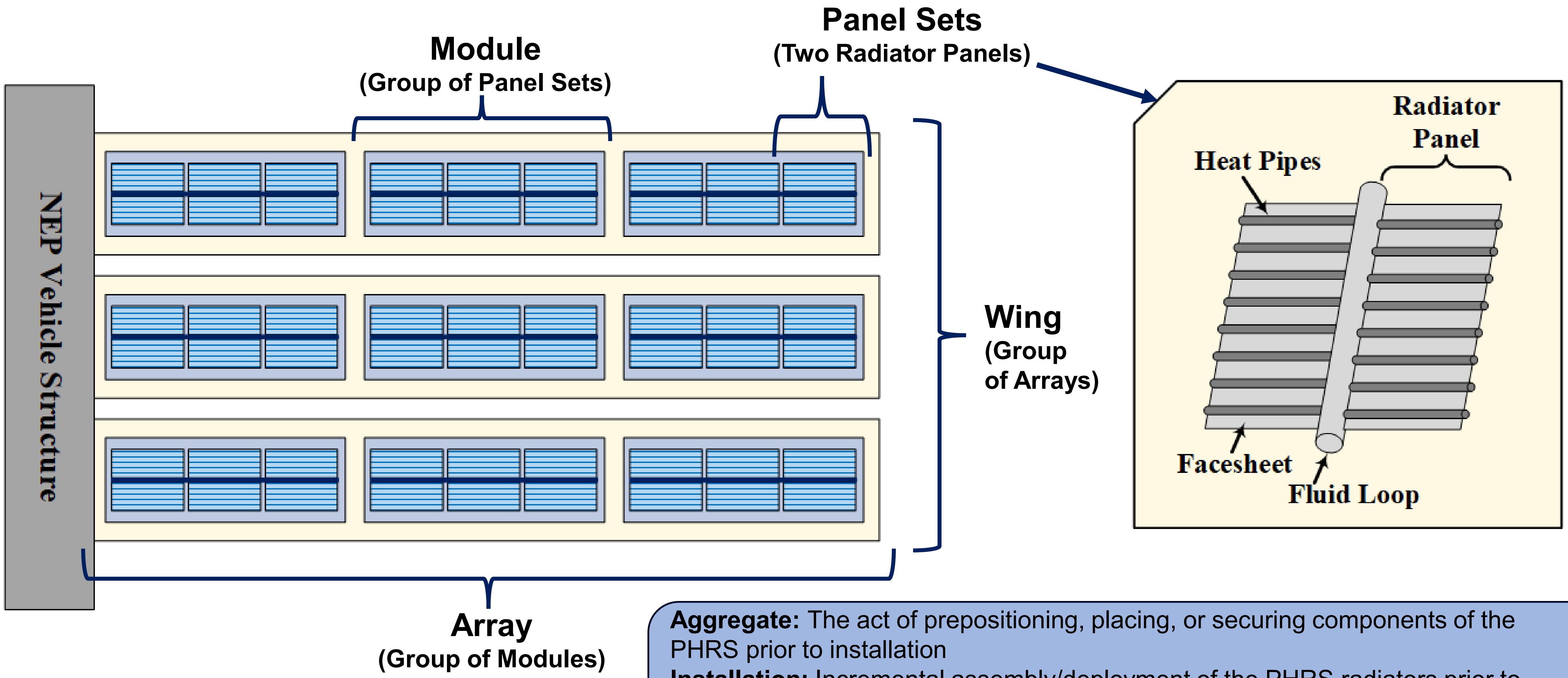
Mars orbit, 1-Sol 250 km perigee,
45° beta angle
Edge to Sun (Horizontal)
Position: periapsis

Min
Plate = 3 K



Interplanetary Space
0° beta angle
Edge to Sun

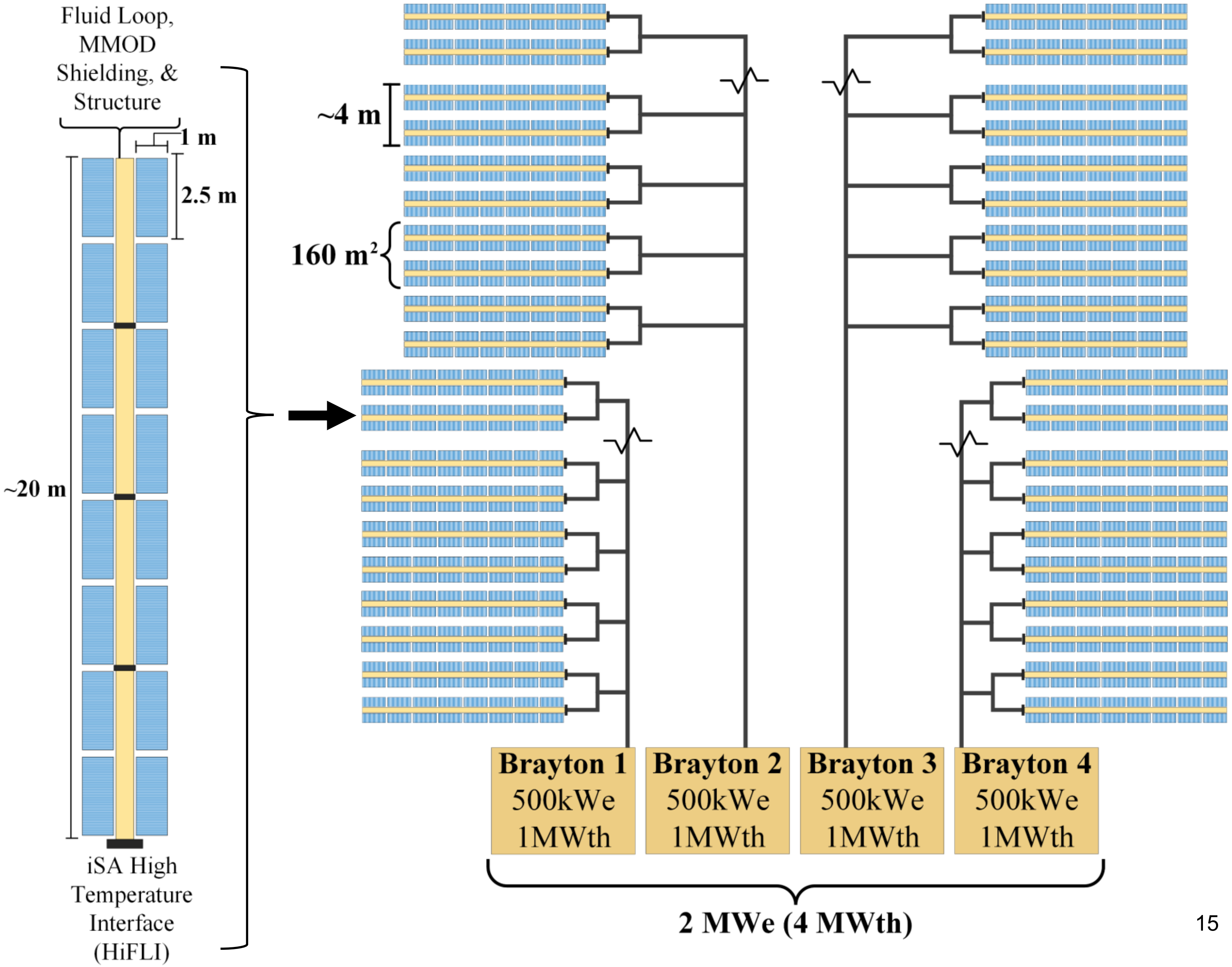
Terminology



Aggregate: The act of prepositioning, placing, or securing components of the PHRS prior to installation
Installation: Incremental assembly/deployment of the PHRS radiators prior to reactor startup
Commissioning: Achievement of an operational PHRS that acquires, transports, and rejects, waste heat in-line with reactor startup

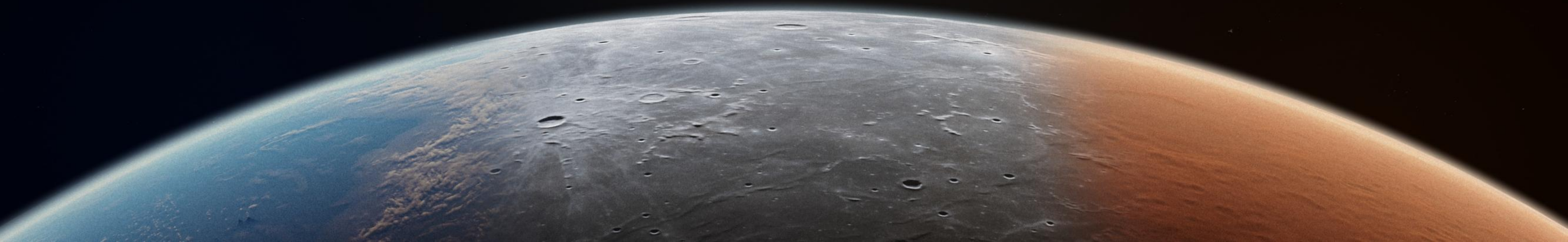
Power Requirements and Waste Heat

- Need around $2MW_e$ for Mars transport
  - Resulting in $\sim 4MW_{th}$ waste heat
  - Four Braytons at $500kW_e$
- Approximate total surface area per Brayton: $800m^2$ ($3200m^2$ total)
  - Four Brayton Engines can add redundance to the system
  - Allows for scalability
- Can be broken down to an array of 16 radiator panels
  - Panels are 1m x 2.5m
  - Because of the temperature of the fluid loop the radiator panels need to be designed with different heat pipe parameters depending on location along array
    - *All heat pipes are titanium with water*



MMOD = Micrometeoroid and Orbital Debris

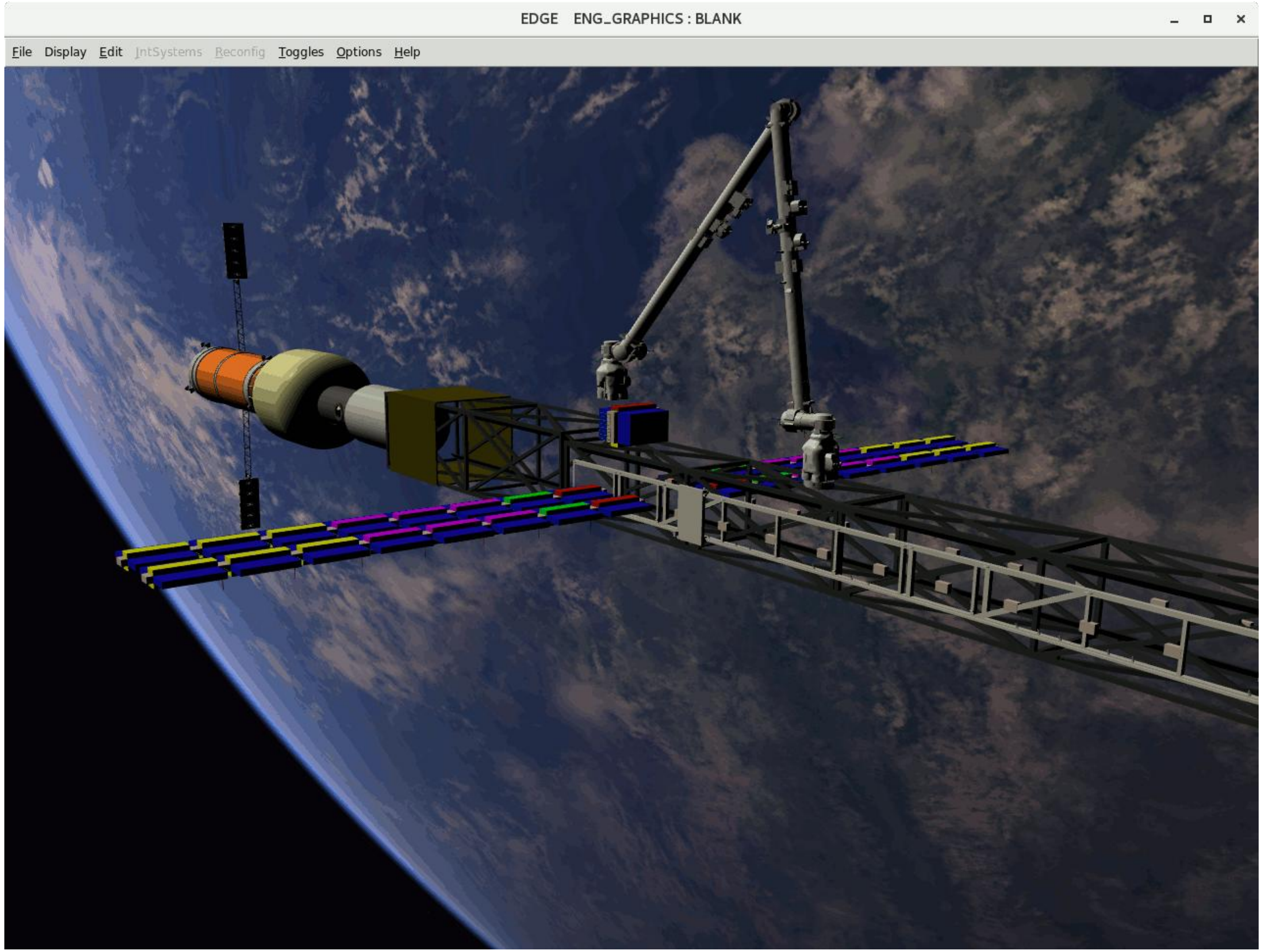
Subdivision Work for Radiator Area and Fluid Loop



Considerations for in-Space Assembly

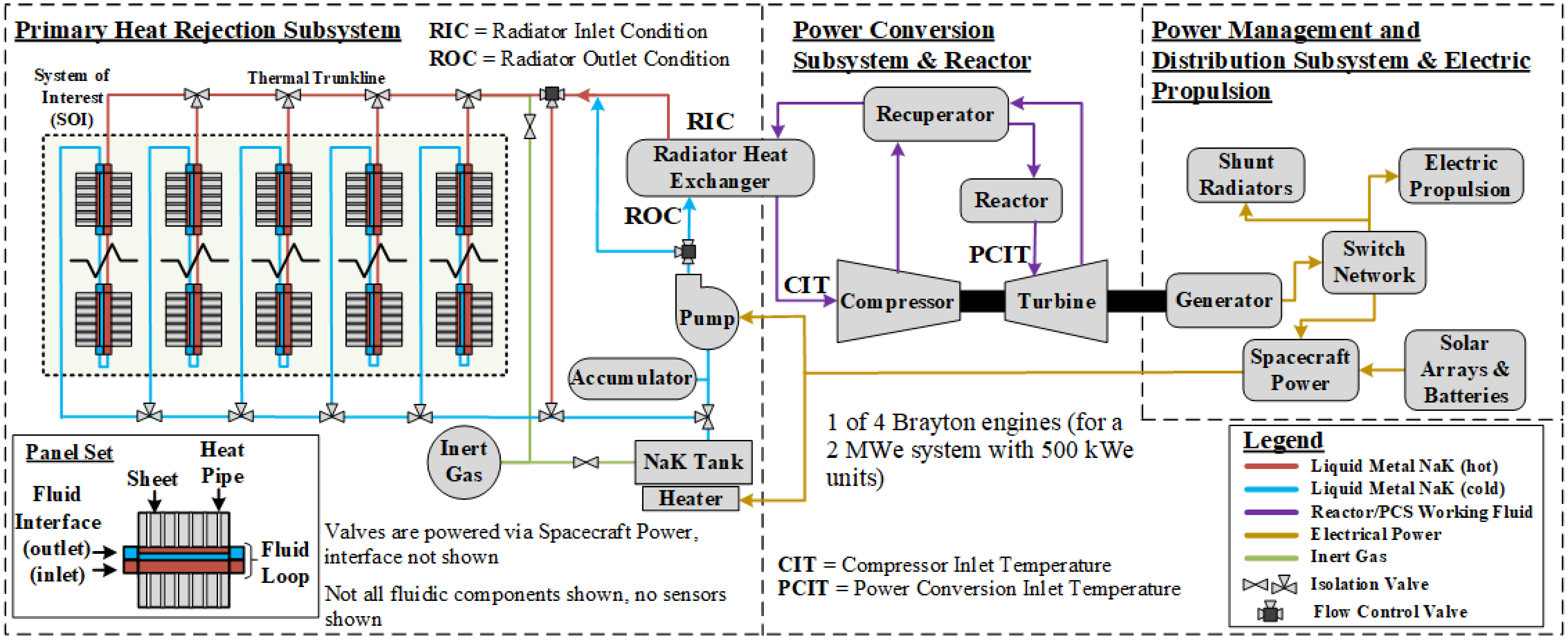
Advantages of in-Space Assembly (iSA)

- Using robotics can help reduce risk to astronauts
- Modular units provide scalable system architecture that can support a range of mission concepts
- Reduced mass improves overall vehicle performance
- Individual components can be repaired or replaced as needed
- Multiple launch vehicles can be used, reducing dependence on any single launch option



System of Interest with connected Subsystems

- Parameters for the radiators are connected to the fluid temperatures of the Power Conversion Subsystem & Reactor

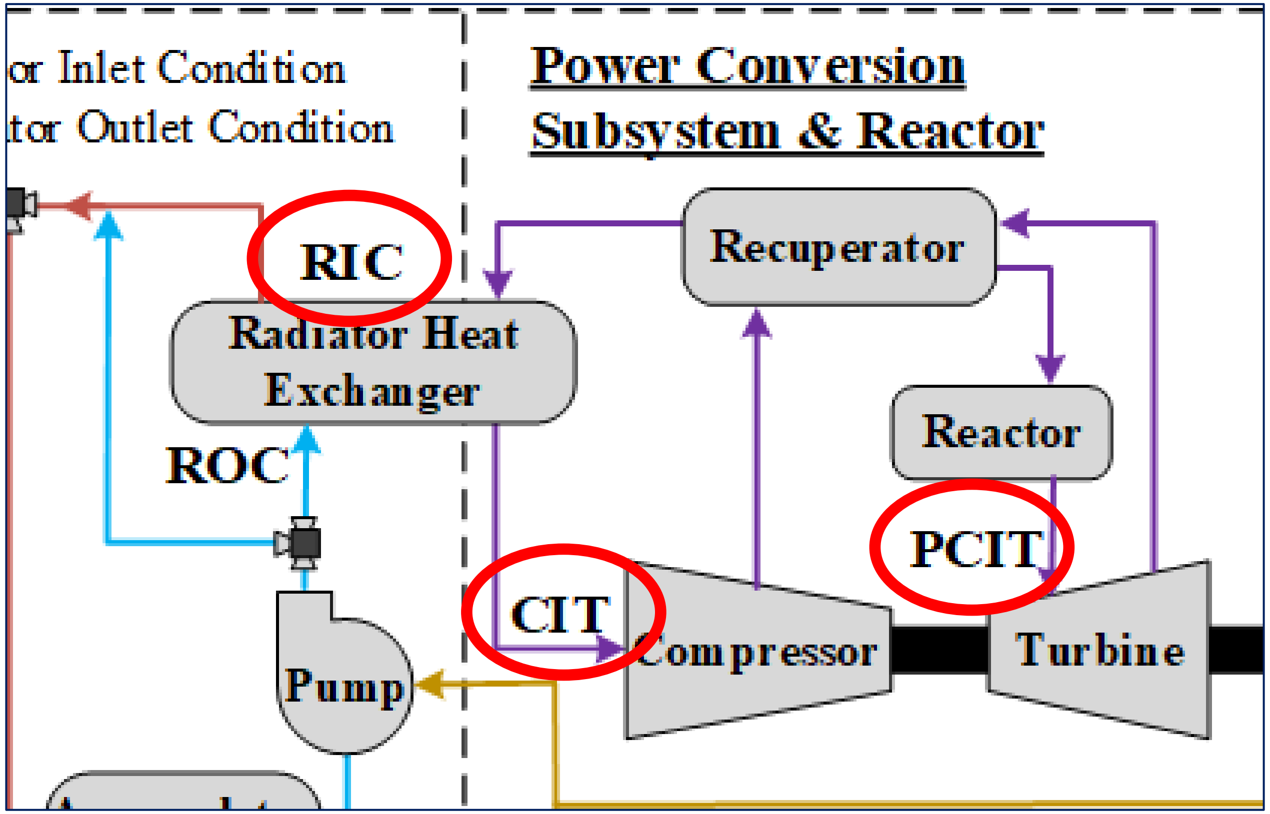


Thermal Trade Studies

- CIT defines outlet temperature of the PHRS
  - Typically found to be 200K lower than RIC
- Increasing PCIT improves power conversion
  - But is limited to 1200K by turbine and reactor materials
- Water based heat pipe technology
  - High TRL
  - Operate up to 550K
  - If the RIC >550K the ROC can be loop back to reduce the temperature
- Result of balancing the TRL for components, reducing mass, and using a PCIT of 1200K
  - RIC = 550K
  - CIT ~330K

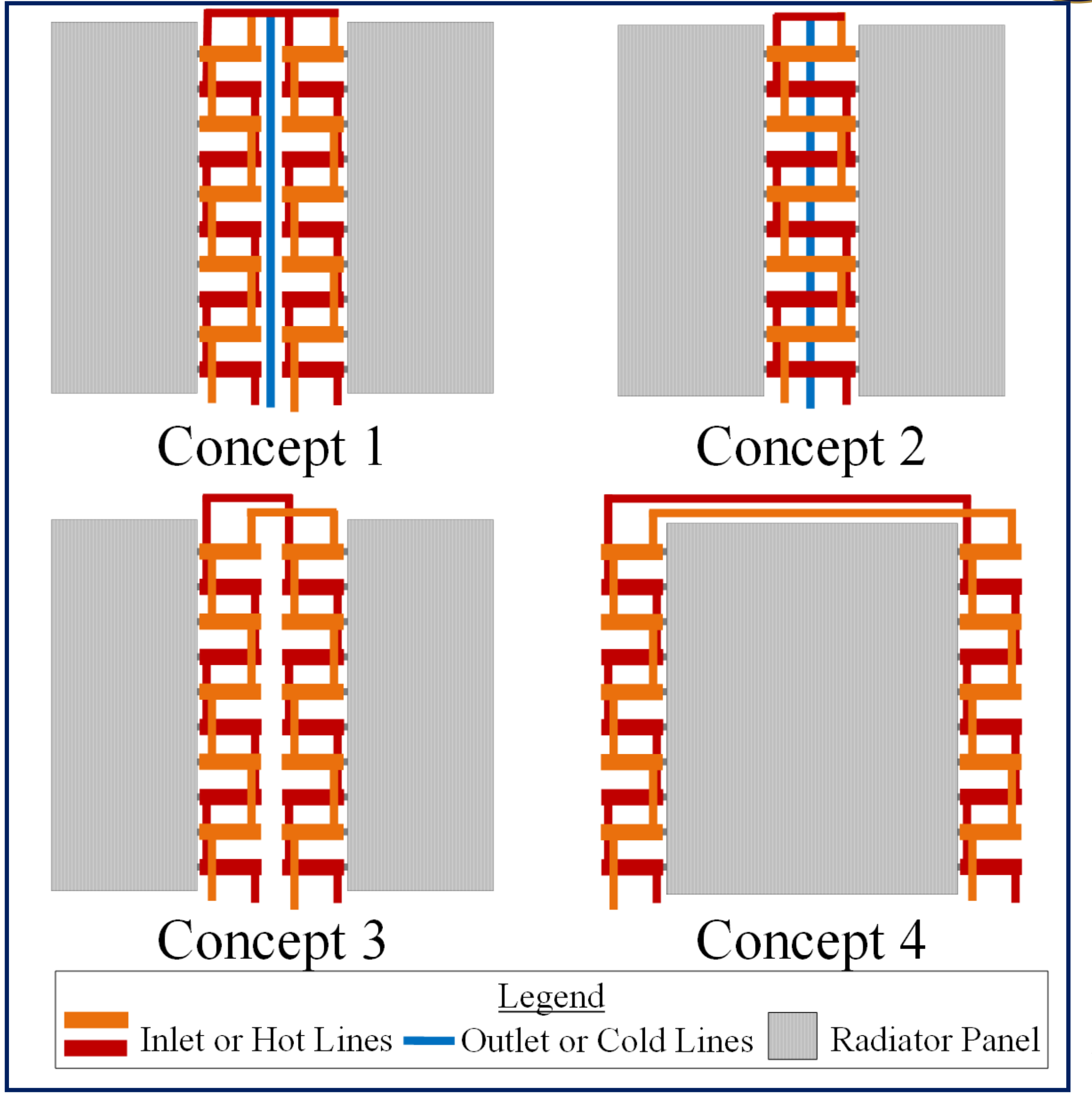
Key items to note

RIC = Radiator Inlet Condition
CIT = Compressor Inlet Temperature
PCIT = Power Conversion Inlet Temperature
ROC = Radiator Outlet Condition



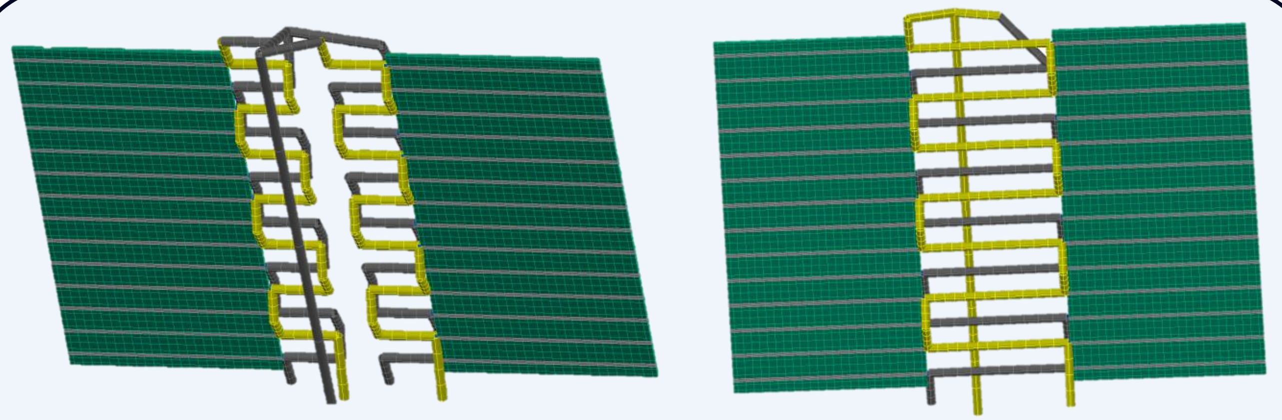
Fluid Loop Routing Concepts

- ➢ Started with 2nd GEN Radiator Demonstration Unit (RDU)
  - Grade 2 Commercially Pure Titanium heat pipes with water
  - Difference from RDU – with the absence of gravity, heat pipes can only be 1m long for optimal efficiency
  - Facesheets: 1m x 2.5m
- ➢ Stainless Steel 304L fluid loop with NaK-78 as the working fluid
- ➢ Evaluated four concepts as potential designs for the fluid loop and heat pipe evaporator section interface
  - Concept 2 was identified as the ideal option



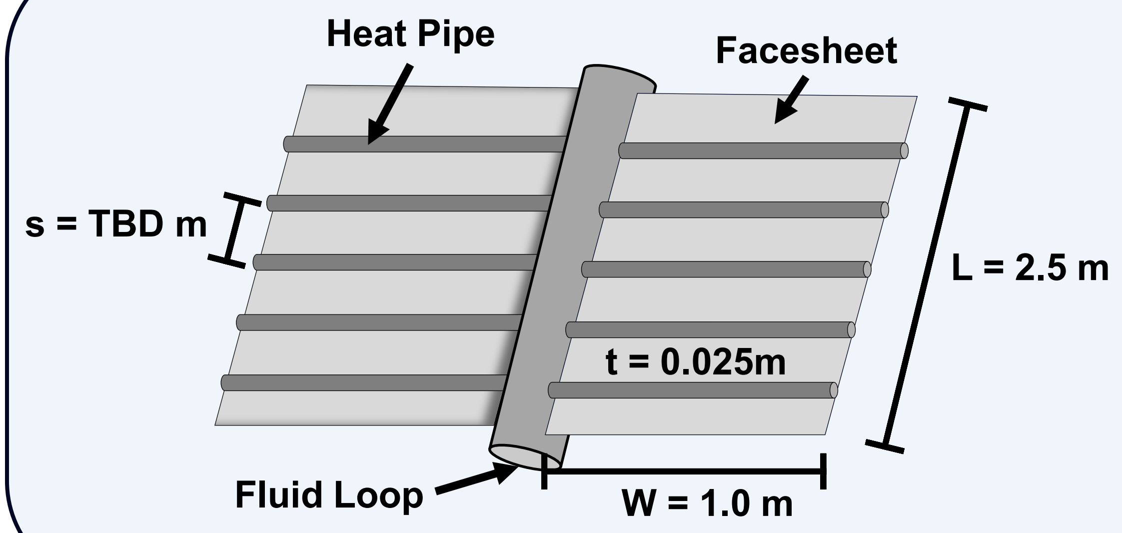
Radiator Panel Thermal Modeling

- 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
- Multi-Layer Insulation (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

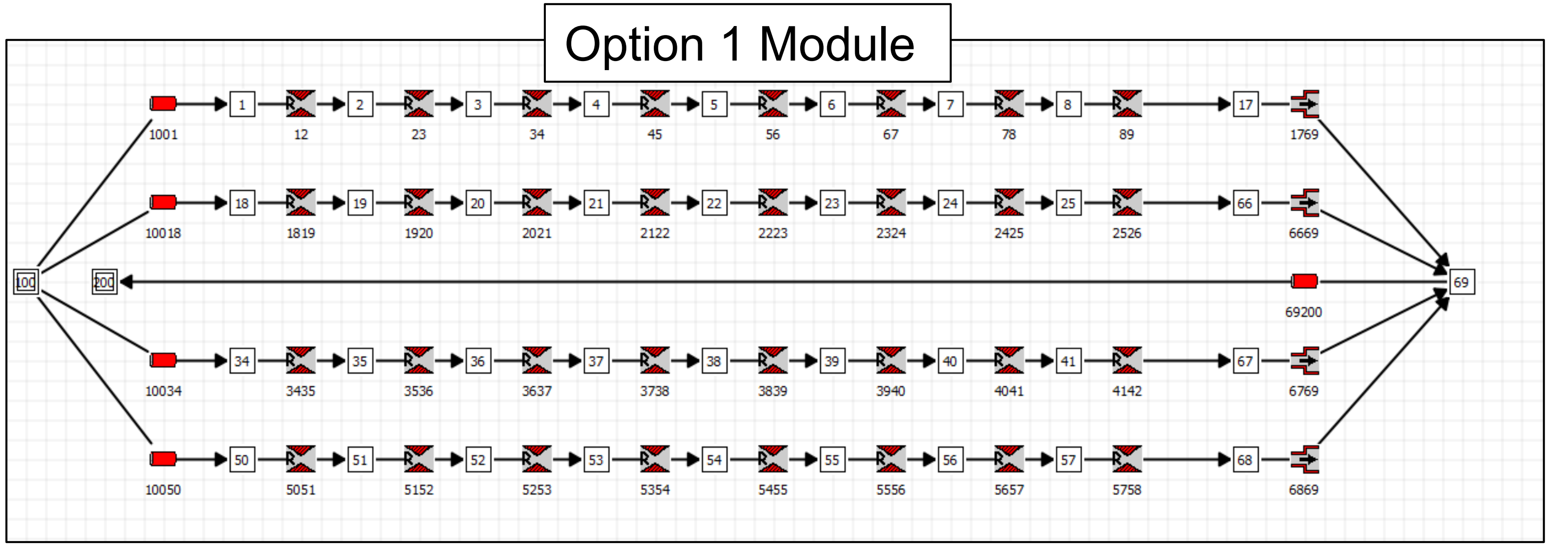
Concept 2 Panel Set



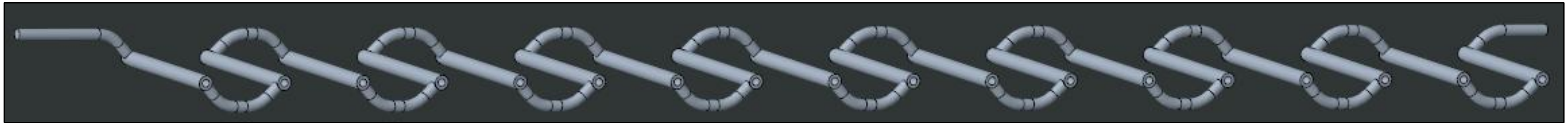
Panel Set

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 Generalized Fluid System Simulation Program (GFSSP)



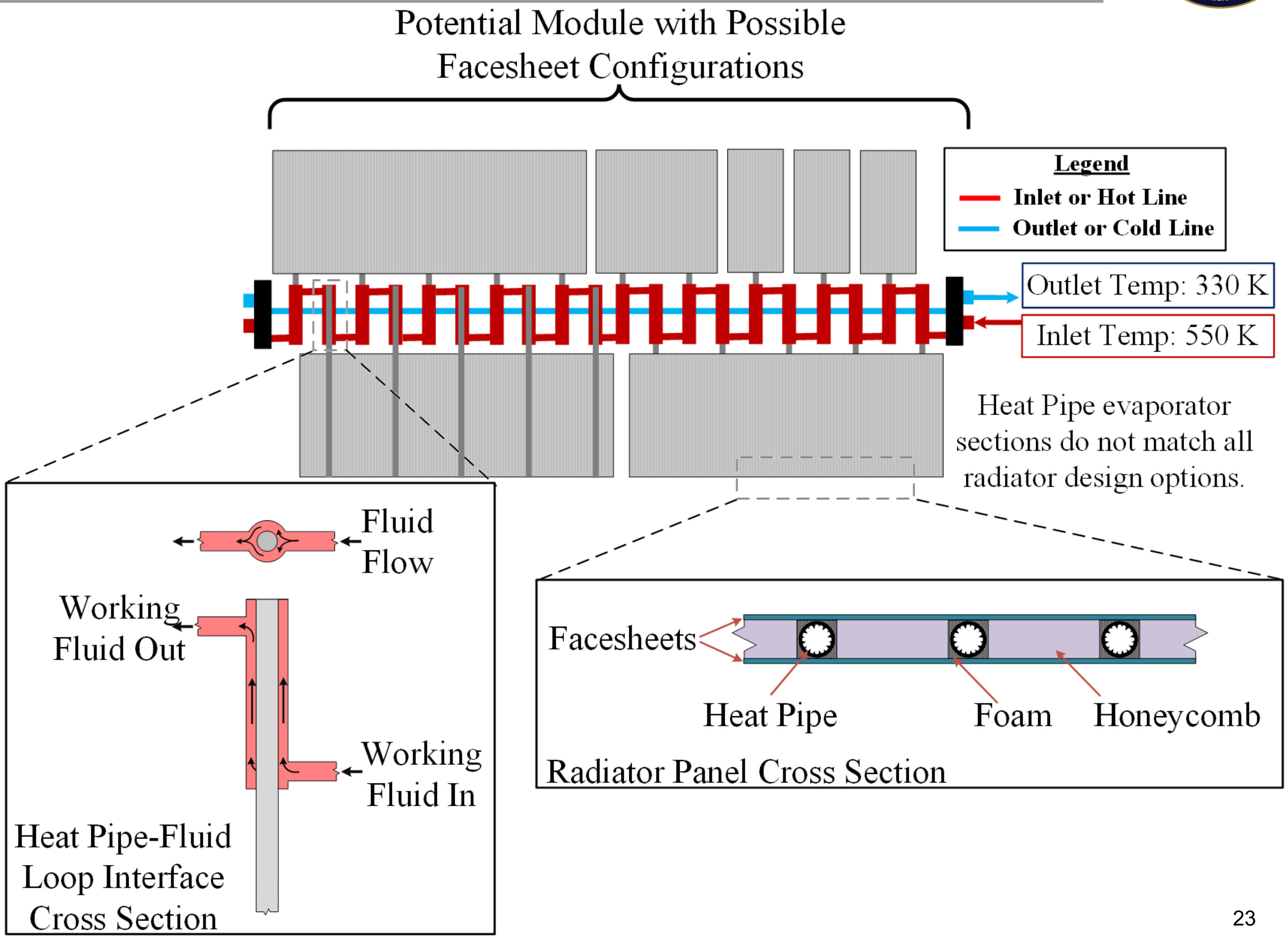
Model for predicting pressure drop across array



Model for predicting pressure drop across panel

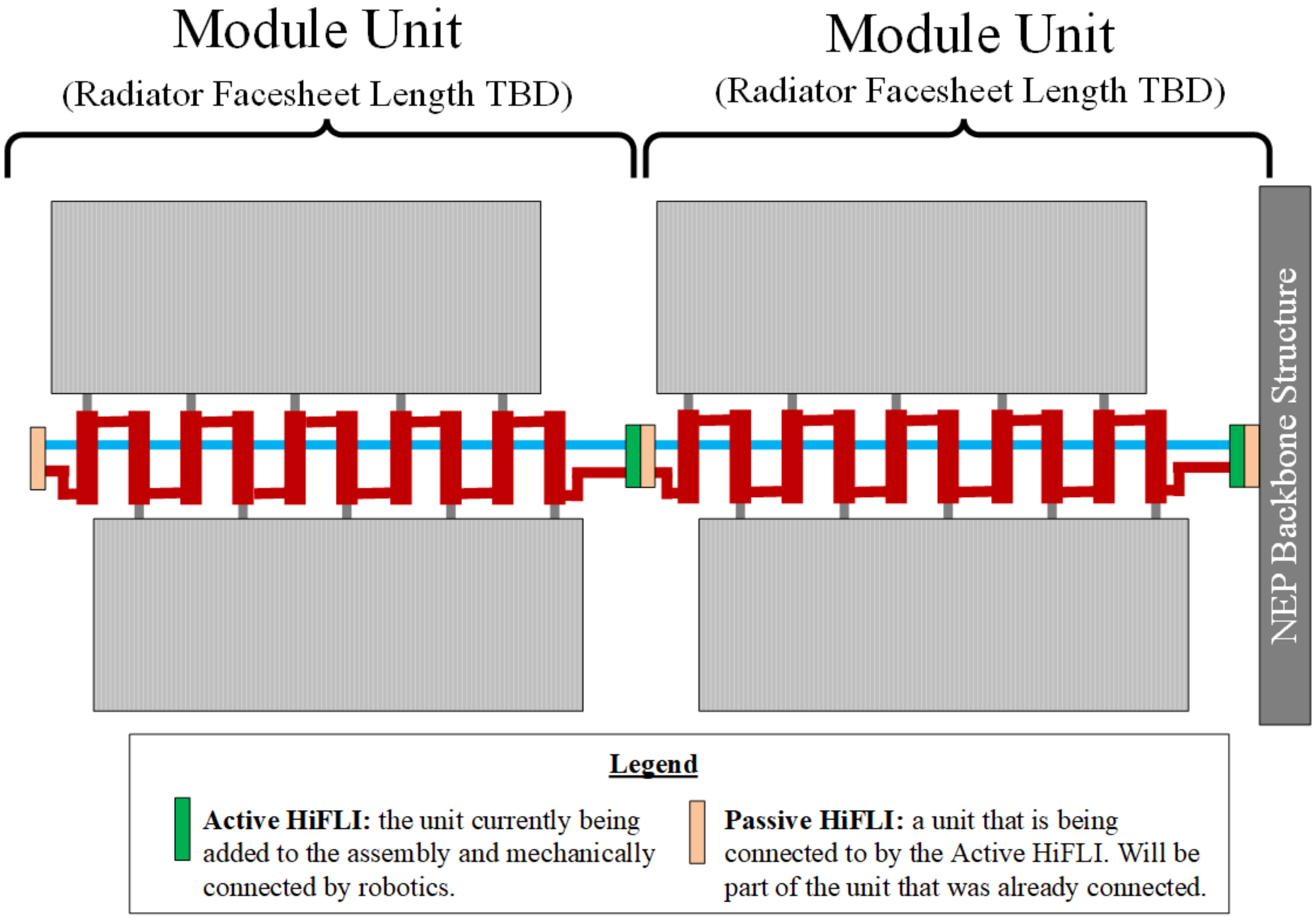
Heat Pipe Design, Analysis, and HFC

- With the modification to the 2nd GEN RDU heat pipe design was addressed to increase efficiency
  - Includes axial groove internal surface
  - Three different diameters and two different operating temperatures
- Focus was given for the Heat Pipe-Fluid Loop Connection
  - Three design considerations
    - *Annuar*
    - *Coil*
    - *Serpentine*



High Temperature Fluid Interface (HiFLI)

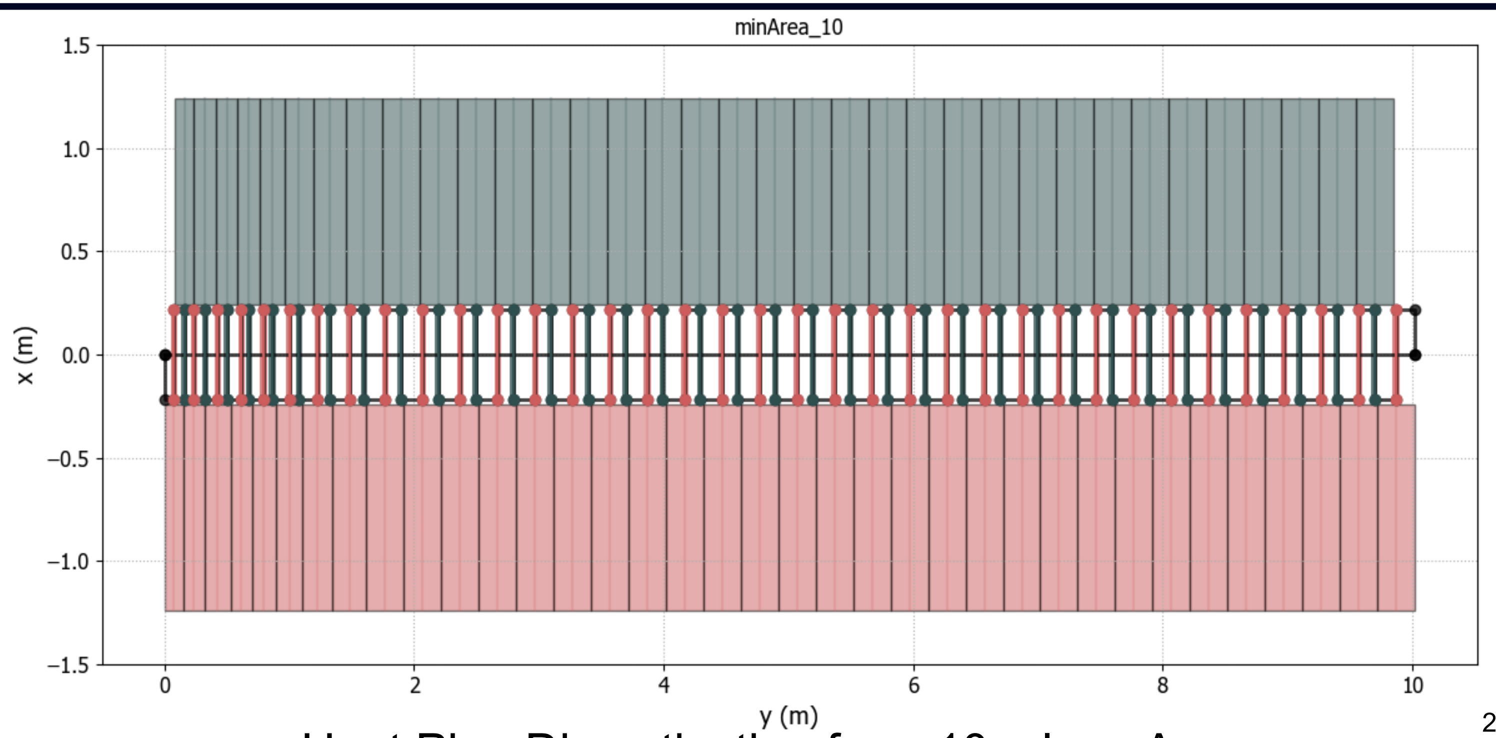
- Fluid connectors are required for providing mechanical and fluid connection between panels and between an array and the truss
  - Two halves will be brought together by the manipulator arm
  - Fluid interface halves will include a carrier plate with alignment rods to control alignment
  - Final connection will be a mechanical connection that is made robotically
    - *This will be reversible for repair and replacement*



Fluid Loop Routing and Panel Configuration - Update

- The 1m x 2.5m facesheets were modified to be the full length of the array and a heat pipe discretization study was conducted for a variety of array lengths
  - Was followed by dividing the full array length into the modular units with the following considerations
    - *Robotic arm reach*
    - *Launch fairing dimensions*
    - *Support structure and number of HiFLI units*

- Fluid loop routing was simplified
  - Became one hot line with a serpentine route
  - Future work will need to evaluate facesheet configuration
    - *Thermal expansion mismatch between fluid loop and facesheet*



Heat Pipe Discretization for a 10m long Array

Conclusion

- MARVL has several purposes
  - NASA Early Career Initiative funded to be designed for early career engineers and researchers to learn about project management and team leadership
  - Technology development focusing on the NEP high-power radiator array and include in-Space Assembly in the design

- Project goal is to have scalable radiator arrays that can take advantage of in-Space Assembly for the NEP Mars transit vehicle
  - Slight modification will be needed

- By the end the team will have a well-defined process for development and recommendations for future work

MARVL

Modular Assembled Radiators for NEP VehicLes

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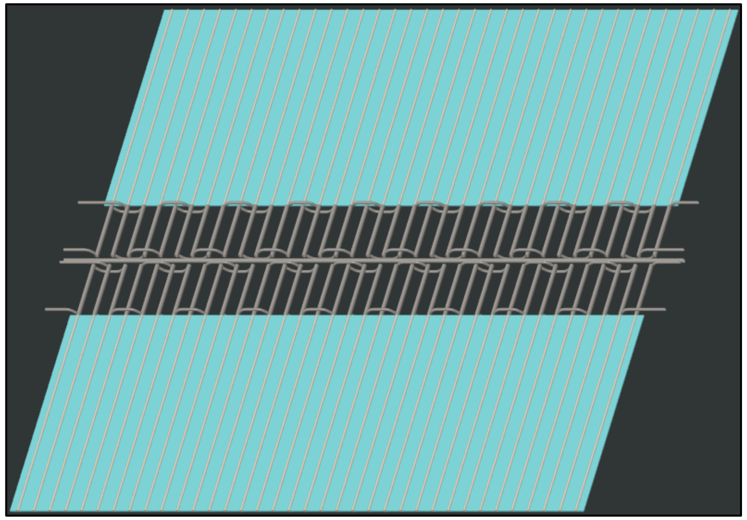
Backup

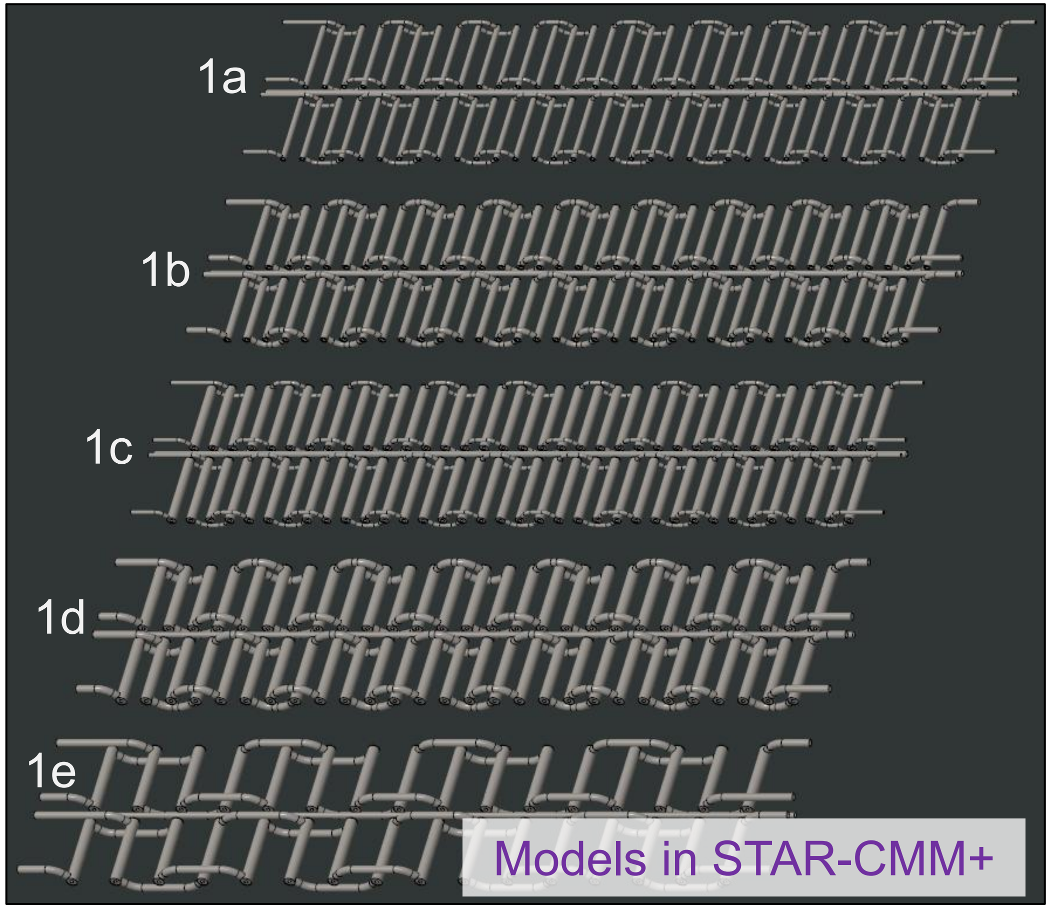
Fluid Line Mass and Volume

- 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