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

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Nuclear Electric Propulsion (NEP) has been considered for crew and cargo class missions to Mars for more than six decades. The Primary Heat Rejection Subsystem (PHRS) of an NEP vehicle expels the megawatts of waste heat generated by the Power Conversion Subsystem (PCS). In previous studies, integrating the majority of the NEP vehicle within a single launch fairing required the use of complex deployable elements and resulted in reduced PCS efficiency. To achieve the necessary radiating area, past design studies have utilized massive multi-wing folding radiators resulting in conceptual PHRS designs that have been widely acknowledged as non-optimal. The Modular Assembled Radiators for NEP VehicLes (MARVL) project is incorporating in-Space Assembly (iSA) into the design process to realize lightweight, modular, and more capable PHRS radiators. Since the project's Authority to Proceed (ATP) date of October 2024, the project team has been developing a modular design for the PHRS radiators that will be suitable for both the Mars mission environments and iSA commissioning operations. This document captures the current progress of the incremental technology development for the thermal components of the MARVL System of Interest (SOI).

Acronyms and Nomenclature

α	=	specific mass per unit power (kg/kW_e)
CFD	=	Computational Fluid Dynamics

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CIT	=	Compressor Inlet Temperature
CP-Ti	=	Commercially Pure Titanium
CTE	=	Coefficient of Thermal Expansion
D&C	=	Design and Construction
DAC	=	Design Analysis Cycles
ECI	=	Early Career Initiative
FMEA	=	Failure Modes and Effects Analysis
FSP	=	Fission Surface Power
FPR	=	Focus Peer Review
GFSSP	=	Generalized Fluid System Simulation Program
HiFLI	=	High Temperature Fluid Interface
iSA	=	in-Space Assembly
ISS	=	International Space Station
KCTE	=	Key Critical Technology Element
LDHEO	=	Lunar Distant High Earth Orbit
LEO	=	Low Earth Orbit
$\dot{m}$	=	Mass Flow Rate
MARVL	=	Modular Assembled Radiators for NEP VehicLes
MMOD	=	Micrometeoroid and Orbital Debris
MTV	=	Mars Transit Vehicle
NaK-78	=	Sodium Potassium
NEP	=	Nuclear Electric Propulsion
NRHO	=	Near Rectilinear Halo Orbit
PCIT	=	Power Conversion Inlet Temperature
PCS	=	Power Conversion Subsystem
PHRS	=	Primary Heat Rejection Subsystem
$R_{n,m}$	=	$\text{Radiator}_{\text{fluid loop number, panel number}}$
R&D	=	Research and Development
RDU	=	Radiator Demonstration Unit
RIC	=	Radiator Inlet Condition
ROC	=	Radiator Outlet Condition
RXS	=	Reactor and Coolant Subsystem
SLS	=	Space Launch System
SME	=	Subject Matter Expert
SNP	=	Space Nuclear Propulsion
SOA	=	State of Art
SOI	=	System of Interest
STMD	=	Space Technology Mission Directorate
tSRR	=	Systems Requirements Review
TD	=	Thermal Desktop
TMP	=	Technology Maturation Plan
TPM	=	Technology Performance Metrics
TRA	=	Technology Readiness Assessment
TRL	=	Technology Readiness Level

I. Introduction

Nuclear Electric Propulsion (NEP) has been considered for crew and cargo class missions to Mars for more than six decades based on fuel efficiencies 10 to 20 times greater than currently achievable with conventional propulsion. An NEP system is comprised of the five technology elements shown in Figure 1. Recent publications have presented NEP as a sister-like system to Fission Surface Power (FSP) with an initial plan of flying a reactor-driven power system of consequential scale that can lead to both human habitation on the Moon (FSP) and beyond (NEP Mars transit vehicle[MTV]) [1]. Much of the current research for NEP technology has focused on the Reactor and Coolant Subsystem (RXS) and Power Conversion Subsystems (PCS), while other subsystems essential for space nuclear power require additional attention as reinforced by the National Academy of Science, Engineering, and Medicine (NASEM) [2] and NASA Engineering and Safety Committee (NESC) [3] reports that indicated all NEP technology elements are technically immature. In the beginning of fiscal year 2025 the Modular Assembled Radiators for NEP VehicLes (MARVL) project reached their Authority to Proceed date from the Space Technology Mission Directorate's (STMD) Early Career Initiative (ECI) Program and began working with the Space Nuclear Propulsion (SNP) project to develop a portion of the Primary Heat Rejection Subsystem (PHRS) of an NEP MTV. The team utilized the Technology Maturation Plan (TMP) generated by SNP to identify key elements which could be modularized to portion out the approximately 3,000 m^2 radiator surface that is needed to expel the Power Conversion Subsystem's (PCS) waste heat. The TMP addresses development strategies for each NEP technology element and outlines subsystem design metrics, candidate component technologies, and incremental development milestones.

The PHRS has three key functions; (1) accept waste heat, (2) transport waste heat, and (3) radiatively reject waste heat to space. During nominal PHRS operations a thermal trunkline accepts waste heat via a heat exchanger with the PCS and transports the waste heat (typically with a pumped liquid metal working fluid) to radiators which then radiatively reject the heat to space.

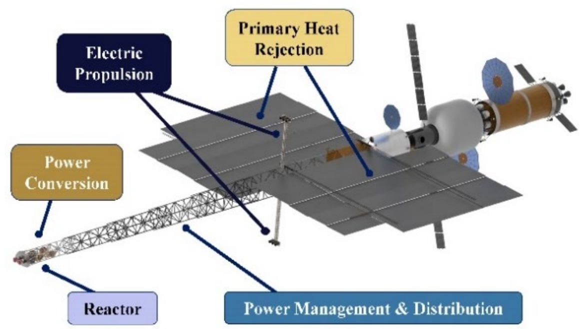

Figure 1. NEP Critical Technology Elements.

Prior to these operations, the PHRS must be launched and commissioned in space in-line with the reactor startup power profile. Previous mission concepts mandated the entire NEP system (radiators, reactor, truss, electric propulsion, and propellant) be packaged under a single Space Launch System (SLS) 8.4 m fairing and then deployed in space [4]. The James Webb Space Telescope (JWST) mirrors represent the state of the art (SOA) for this commissioning method as they were folded to fit inside a single payload fairing and then deployed on-orbit with many complex single-point failure mechanisms [5]. Due to the required PHRS radiator area (~3,000 m^2), packaging the radiator arrays in a single launch fairing with the rest of the NEP system limits available surface area and forces tri-wing or quad-wing array configurations with heavy deployment mechanisms.

Multi-wing arrays must compensate for both incident solar flux and radiative inefficiencies caused by wing-to-wing view factors (Figure 2a). Highly reflective coatings (low solar absorptivity) are therefore necessary to reduce the heat load imparted by incident solar flux [6]. However, these coatings are not currently available in the temperature range of interest despite significant R&D [6]. Additionally, multi-wing arrays must limit the total radiator surface area by reducing PCS cycle efficiency which drives total NEP mass (excluding the chemical stage) past the payload capacity of even super heavy lift launch vehicles.

Collectively, these characteristics of prior conceptual approaches significantly constrain the design potential of PHRS and limit flexibility in achieving the Key Performance Parameter (KPP) for the specific mass per unit electrical power produced (α, kg/kWe) to overcome what is often termed "the tyranny of the radiator." Single co-launched PHRS designs and commissioning schemes are acknowledged as non-optimal. They constrain architectural flexibility, limit vehicle performance, and have been identified by Glenn Research Center (GRC), the SNP project, and NASA Headquarters as a major NEP architectural risk driver [4, 6, 7].

In contrast, a planar bi-wing array design (Figure 2b) eliminates wing-to-wing view-factor losses and can be flown edge-on to the sun to minimize incident solar flux, resulting in a 20 to 40% dry mass reduction when compared to tri-wing and quad-wing options [6, 8]. This decrease in dry mass reduces the required mission propellant mass by dozens of metric tons, which in turn alleviates vehicle refueling requirements. Flying edge-on to the Sun will eliminate the need for currently non-existent flight-demonstrated, high-emissivity radiator surface treatments. Despite these benefits and like multi-wing arrays, a planar bi-wing array sized to reject reactor waste heat and co-packaged with the rest of the NEP system exceeds the payload capacity of a single launch fairing [6].

The planar bi-wing PHRS configuration becomes possible when alternative methods for achieving large structures in space are considered. As stated in the NEP TMP, incorporating in-Space Assembly (iSA) into PHRS design enables the planar bi-wing configuration, provides launch service flexibility, reduces the structural mass required to support launch loads, offers the potential for repair and refurbishment, and eliminates the need for heavy and complex deployment mechanisms. The resulting scalability and mass efficiency offered through iSA could also enable a higher power and thrust level NEP which would reduce Mars transit duration and thus astronaut radiation dosage therefore improving crew safety [6]. Utilization of robotics for PHRS commissioning also frees astronauts to do other operations such as science activities.

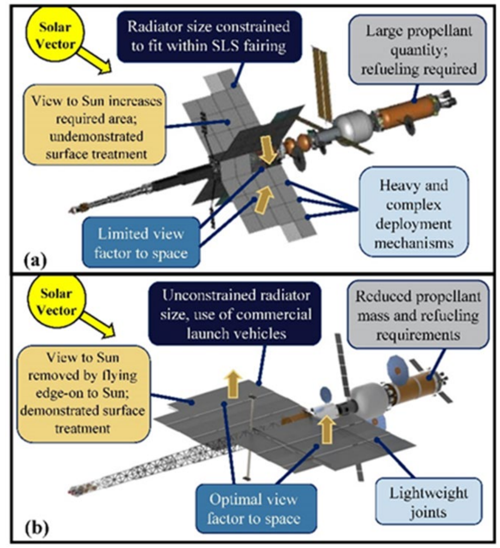

Figure 2. Quad-wing versus Bi-wing.

The International Space Station (ISS) radiators provide the closest SOA comparison to the NEP PHRS in terms of both size and commissioning approach. For the ISS, six radiator array modules were separately launched and then robotically attached to the central station truss. Installation operations included structural, fluidic, and electrical connections; a clear demonstration of the feasibility of iSA for large heat rejection systems. However, ISS radiators do not meet NEP PHRS requirements including areal density, working fluid material compatibility, maximum temperature rating, heat rejection capability, or environmental compatibility.

II. MARVL Background

A. Target Application and Relevant Environments

Technology development is undertaken to enable or enhance future missions. The target application represents the practical intended use of the technology and forms the foundation for all subsequent development activities. MARVL's target application, which drives the current development scope and requirements, is a crewed hybrid NEP/chemical Mars opposition-class mission. Secondary applications include NEP uncrewed cargo and lower-power science vehicles. The requirements of the target application envelope much of those derived for the secondary applications, thus making it a more conservative requirement source.

Opposition-class Mars missions utilize high energy trajectories to achieve round-trip mission times of approximately two years with brief ~50 day stay times at Mars (Figure 3). These opposition-class missions are often augmented with a Venus flyby either on the outbound or inbound trajectory to reduce propulsive energy requirements. The two-year round-trip durations of opposition-class opportunities make them an ideal choice for initial crewed missions in terms of vehicle reliability and crew safety especially regarding the temporal risks presented by space environments. The propulsive energy requirements of the 2039 opposition-class mission opportunity are intense, so an MTV designed for this opportunity supports a wide range of less challenging missions.

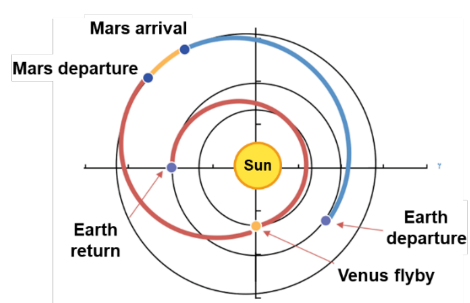

Figure 3. Opposition-class Mars mission [17].

Relevant mission phases include ground processing, launch to low Earth orbit (LEO), aggregation, installation and commissioning in LEO, as well as post start-up operations through the possible mission locations. These locations include LEO, Near Rectilinear Halo Orbit (NRHO), Lunar Distant High Earth Orbit (LDHEO), interplanetary space, Mars orbit, and a Venus flyby. Multiple orbit altitudes, orbit eccentricities, and trajectories are possible for each location.

The natural and induced environments exposed to the PHRS during the target mission inform system requirements and future relevant environment demonstrations necessary to meet Technology Readiness Level (TRL) 4, 5, and 6 criteria. MARVL has leveraged environmental specifications from robotic Mars missions, findings from previous Mars architecture studies, and SNP input to generate an environmental specification. The subsets of the total mission environments that present significant risk to system operations (or relevant environments) include thermal extremes, vacuum, Micrometeoroid and Orbital Debris (MMOD), radiation, launch loads (vibration and acoustics), in-space loads, and microgravity (thermal fluid performance). The relevant environments focus design, analysis, testing, and demonstration activities on the environmental conditions that stress novel aspects of the technology.

Design and analysis activities have ensued to estimate the impacts and requirements imposed upon the PHRS due to these relevant environments, but most of these results are not presented here. Regarding the thermal environment, a panel was modeled using CRtech's Thermal Desktop (TD) for each mission location to estimate the environmental heat flux absorbed by the PHRS in worst case hot and cold conditions (Figure 4). Surveys were conducted by various resources and NASA documentation to identify the hot and cold values of nearby heating sources in the space environment [9, 10, 11]. The values were used as inputs for the TD model. Six radiator orientations were modeled to investigate performance in this environment for unpowered and powered reactor states. The analysis produced environmental sink temperature profiles and heat rejection capability curves for all ten modeled orbits and trajectories, as well as for all six panel orientations.

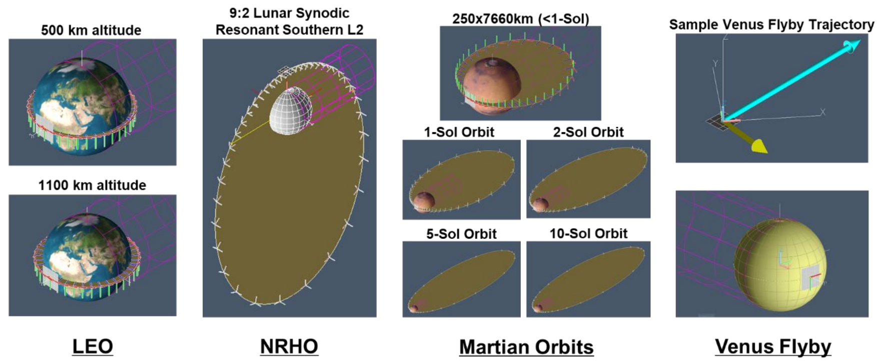

Figure 4. Thermal environments of interest.

Subsequent analysis of the heat rejection capability requirements at the corresponding mission locations and reactor power levels resulted in the identification of ideal panel orientations throughout the mission. This selection reduced the total number of cases from 328 to 35, and the selected cases can be executed with the full vehicle model in future studies. The complete envelope of thermal environments for the possible mission locations and trajectories, based on the selected panel orientations, is summarized in Table 1 and can serve as input for future thermal analyses.

Table 1. Reactor Power State with Corresponding Thermal Environment Extrema.

Reactor State	Objective	Case	Temperature (K)	Location (Specification)	Panel Orientation
Powered Off	Maximize radiator panel temperature, prevent freezing	Hot	298	LEO (500 km, 0º beta angle)	Face to Sun
		Cold	30	NRHO (9:2 lunar synodic-resonant, southern L2 Lagrangian point, 0º beta angle)	Face to Sun
Powered On	Minimize radiator panel temperature, prevent overheating, increase heat rejection	Hot	236	Mars orbit (1-Sol, 250 km perigee, 45º beta angle)	Edge to Sun (horizontal)
		Cold	2.7	Interplanetary Travel	Edge to Sun

B. Key Critical Technology Elements

The MARVL project focuses on a portion of the total NEP PHRS. This System of Interest (SOI) includes: (1) radiator surfaces and heat pipes, (2) fluid loop lines, (3) fluid interface used for the iSA process along the fluid loop line, and (4) the robotic components and capabilities required to install the radiator modules. Outside of the MARVL SOI, the PHRS will include a liquid metal pump, accumulator, PCS heat exchanger, liquid metal storage tank, pressurant gas tank, and fluid management components (valves, filters, etc.). Besides adjacent PHRS elements, other external interfaces to the MARVL SOI include the truss structure, power distribution system, command and data handling system, launch vehicle, and ground support equipment. PHRS elements are shown with interfaces to the other NEP elements in Figure 5.

Not all PHRS elements are new technologies but are rather engineering development items that can reasonably be expected to become available with slight modifications to existing designs. In terms of novel technologies, MARVL conducted a Technology Readiness Assessment (TRA) to identify three Key Critical Technology Elements (KCTE) that require focused advancement to achieve required functional and performance capability in the target application. KCTEs are the technical elements that provide new capabilities or require maturation of existing capabilities that are

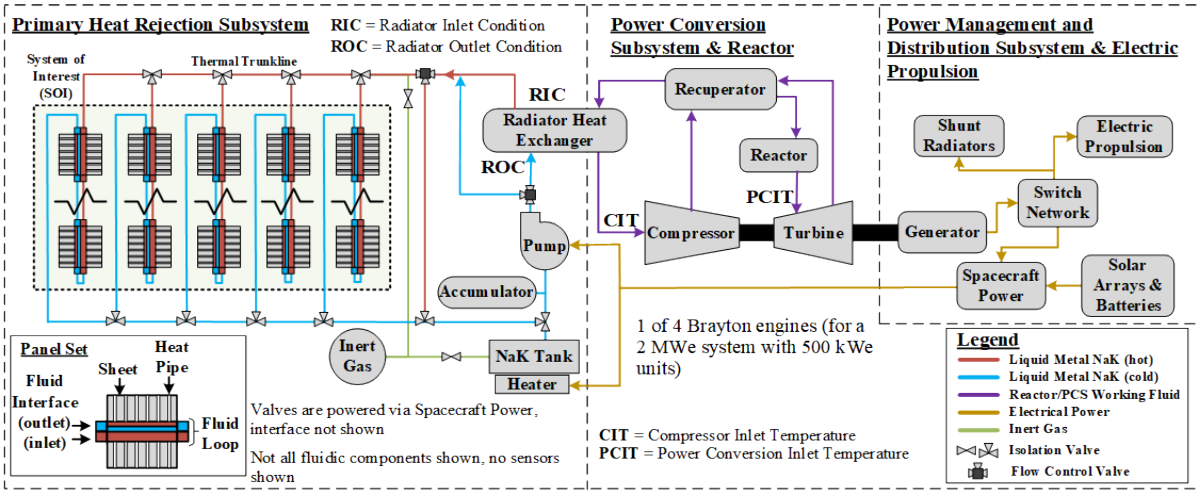

Figure 5. MARVL system context diagram.

key to the success of future system operational requirements. A technical element is designated as a KCTE when one or more of the following apply: novel functions, extended capability, new application, new integration, manufacturing challenge, model/simulation development, major risk contributor, or critical performance driver.

KCTE-1 PHRS Integrated Simulation Framework: A simulation framework to validate the full-scale commissioning operations of the PHRS, assess design feasibility, inform technology development, and support hardware-in-the-loop testing for future ground demonstrations. Model validation will be partially accomplished through hardware test data from sub-components. Completed simulation framework validation will occur during future increments of technology development after sub-scale ground demonstrations.

KCTE-2 High-Temperature Radiator Unit: A modularized collection of radiative heat rejection surfaces compatible with the selected installation and commissioning scheme which could involve robotic manipulation. This includes structural supports, fluidic piping, surface treatments, panel materials, heat pipes, and grapple features. Temperature extremes and working fluids of interest are outside of previously demonstrated spaceflight capability. Radiator unit levels are illustrated and defined in Figure 6.

KCTE-3 High-Temperature Fluid Interface (HiFLI): Connector device enabling reliable in-space installation of radiators to each other and the thermal trunkline. This connector is robotically actuated and facilitates reliable fluid introduction and flow. The temperature extremes and working fluids of interest are outside of previously demonstrated spaceflight capabilities.

C. Terminology

Establishing terminology for the MARVL SOI was critical for communication within the team as well as with stakeholders and interested parties. The terms in Table 2 will be used throughout this paper and are presented here for clarity. Figure 6 is an illustration of the radiator components of the general design. Along with component terminology, the project defined terms with definitions for concept of operation phases as well, found also in Table 2.

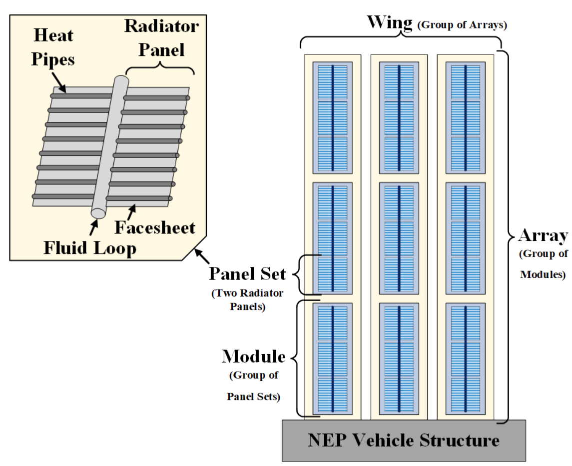

Figure 6. MARVL Terminology.

III. Power Requirements and Waste Heat

A crewed NEP Mars vehicle requires a minimum of around 2 MW_e from the reactor. These requirements combined with the PCS efficiency (25 to 40%) generate around 4 MW_{th} of waste heat to be rejected. To account for redundancy and development flexibility, the PCS was then divided into four Brayton engines that will each generate a nominal 500 kW_e (or 1 MW_{th}) with each engine having a dedicated set of radiator arrays to expel waste heat (Figure 7). MARVL's goal is to divide the radiator wings into

Table 2. MARVL Terminology with definitions.

Term Definition
Thermal Trunkline: Portion of the total high-temperature fluid loop that transfers heat and liquid working fluid (metal NaK-78) from the power conversion heat exchanger to the PHRS
Fluid Loop: Portion of the total high-temperature fluid loop that acquires heat and liquid working fluid (metal NaK-78) from the thermal trunkline and distributes it across the radiators via connections with individual heat pipes
Heat Pipe: Passive thermal transport devices that transfer heat through phase change of an internal working fluid (water)
Heat Pipe to Fluid Loop Interface: Feature encapsulating the evaporator section (heat input) of an individual heat pipe allowing for heat transfer from the working fluid in the fluid loop to the heat pipe
Radiator Panel: Consists of two facesheets and the required number of heat pipes. Approximate size is 2.5 m x 1 m
Panel Set: Two Radiator Panels connected by the Fluid Loop and needed structural supports
Module: A group of two or more Panel Sets that may be assembled in space
Array: A group of two or more Modules
Wing: A group of two or more Arrays
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

segments by designing repeatable iSA modular units for assembly operations in space (see Figure 5). The overall size of the radiators is subject to change as technology matures and data from hardware demonstrations are obtained. The full system will require > 3,000 m^2 of radiator surface area. Including area margin, each Brayton engine will therefore require ≥ 800 m^2 of radiator area.

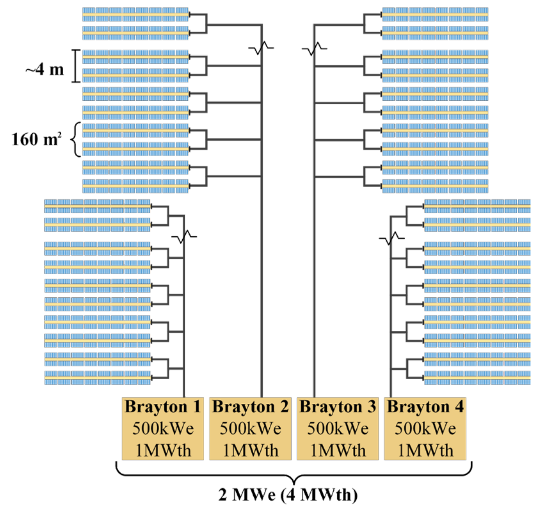

Figure 7. Division for power generation and radiator area layup.

IV. Subdivision for Radiator Surface Area

A. First Year Process

MARVL is funded by the NASA STMD ECI program with a set duration of two years. Design Analysis Cycles (DAC) were used to keep the project on schedule with the first year divided into a Concept Development Phase and an Initial Design Phase, separated by a tailored Systems Requirements Review (tSRR).

The Concept Development Phase studied the design considerations of prior PHRS configurations used in past NEP MTV studies and the advantages or disadvantages of incorporating iSA. With the team consisting of early career engineers, the concept Development Phase was also used as an educational period to learn about the technical aspects of the PHRS, NEP/Chem MTV, and what will need to be considered for a potential Mars mission. After completing the tSRR, the team moved into the Initial Design Phase and focused on the technical design of the PHRS which involved trade studies and initial design definition. Going into the second year, the team moved into a Preliminary Design Phase that started with a Focused Peer Review (FPR). The Preliminary Design Phase focused on details of the design, assuring that the iSA process is considered, well defined, and meets defined requirements.

The following subsections of this document will focus on the work conducted over the first year in preparation for the Preliminary Design Phase in the second year.

1. Considerations for in-Space Assembly

Incorporating iSA into the design facilitates configuration and launch manifest flexibility, which aids in maintaining resiliency to uncertainty in vehicle requirements and radiator technology performance. Designing for iSA opens the NEP vehicle to paradigms that are infeasible using traditional deployment operations. Additionally, larger PHRS become possible when vehicle components can be launched aboard multiple vehicles. SNP is also considering iSA as a method to reduce risk by distributing system components across launch vehicle capabilities and assembling in space instead of relying on a single launch fairing for delivery to orbit [6]. Through iSA, modular units enable system scalability for alternative mission concepts by reducing redesign required for other vehicle types compared to bespoke deployable designs. Modular units may further benefit from deployment mechanisms by improving launch packaging without limiting vehicle size. ISA also provides the opportunity to replace or repair damaged units without replacing the entire system.

Additionally, assembly of modules can reattempt a failed connection compared to critical deployment mechanisms that are incapable of trying again. To prepare the MARVL HiFLI component for use in the iSA process, the operation requires significant testing to produce repeatable, leak-resistant fluid connections. While extra testing is needed, the scale of the tests can be reduced with iSA. Massive deployment test facilities would not be required, as was the case for JWST solar shields and other deployment mechanisms [5].

2. Thermal Trade Studies

The PHRS is heavily integrated with the other NEP subsystems, and the full NEP system must be considered when performing thermal trades. Since the PHRS can make up half of the total NEP system mass (40 to 60%), the optimum mass of the NEP system is not necessarily the optimum PHRS mass. The masses of the PCS and RXS elements are estimated along with the PHRS mass to evaluate the thermal trades at a system level. The operating temperatures of the Brayton cycle are the most important parameters in determining the performance and mass of the NEP system. The thermodynamic cycle is defined by the low temperature or Compressor Inlet Temperature (CIT) and the high temperature or Power Conversion Inlet Temperature (PCIT). Increasing PCIT greatly improves power conversion efficiency and system mass, but this temperature is currently limited by turbine and reactor material compatibility to 1200 K [13]. The CIT defines the outlet temperature of the PHRS, and there is an optimum value that optimizes NEP system mass. This optimum is a balance between increasing power conversion efficiency and maximizing heat rejection per area in the radiator. Lowering the CIT will increase system efficiency, resulting in lower total heat load to be rejected, smaller and lower power reactors, lower mass flow rate and smaller heat exchangers, and turbomachinery. The cost is a lower radiating temperature and therefore requires a much larger radiator. It may appear that the radiating area, being proportional to temperature to the fourth power, would dominate this optimization as the system efficiency is only linearly proportional to the temperature; however, all of the secondary effects (including smaller reactor, heat exchangers, and turbomachines) of the increased efficiency result in a much more balanced optimization. For a set CIT and PCIT, the inlet temperature of the PHRS is primarily a function of turbomachine and heat exchanger efficiency and is not necessarily a design variable. The PHRS inlet temperature will typically be around 200 K higher than the CIT.

Another important part of the thermal trade is the technology development needed to reach higher temperatures. Titanium water-based heat pipes are at a high TRL (level 6) and can operate up to 550 K. Above this temperature heat pipe TRL is much lower. From 550 K to 650 K there are few available heat pipe fluid options, and fluids that can be used such as halides or sulfur-iodine are very low TRL. Above 650 K, cesium can be used as a heat pipe fluid and has a higher TRL than a halide or sulfur-iodine but lower TRL than water heat pipe. To avoid reliance on the lower TRL heat pipes, options such as using a pumped fluid loop in place of heat pipes or mixing some of the radiator outlet with the radiator inlet to reduce the inlet temperature will allow hotter inlet temperatures with less technology development risks. Using pumped fluid loops increases MMOD risk while fluid re-circulation negates the lower energy per area benefit of a higher CIT. In addition, increasing the CIT has diminishing returns on its own. In order to realize the full benefit of a hotter radiator, the PCIT temperature needs to increase as well, which also requires technology development investment.

When optimizing the NEP system for lowest mass and considering the TRLs for the radiator as well as the PCS and RXS, it was determined that the CIT should be ~330 K. This corresponds with a PCIT of 1200 K and a radiator inlet of 550 K. This reduces the technology development or fluid re-circulation needed for the higher temperature radiator, by staying in the range of water heat pipes. The radiator temperature does not necessitate technology development on the hot end of the system but can still be paired with a higher PCIT for higher efficiency if high temperature hot end components are matured. The 330 K to 550 K radiator temperature with a 1200 K PCIT for a 2 MW_e system will result in 34% thermal efficiency for the PCS, with 4 MW_{th} being rejected via ~3000 m^2 of radiating area.

B. Fluid Loop Routing and Panel Configuration

MARVL is leveraging and modifying existing radiator fluid loop designs which were developed during previous GRC efforts. The water-based heat pipes are constructed from Grade 2 Commercially Pure Titanium (CP-Ti) and are embedded in a Stainless Steel 304L fluid loop with alkali-metal NaK-78 as the working fluid. The outlet and inlet temperature for each radiator array is 550 K and 330 K respectively. The current radiator modular unit consists of two panel sets, each with two panels, with fluid loop lines running between the panels and HiFLI units at each end for assembly operations (Figure 8).

Initially, four fluid loop routing designs were selected for consideration. From these options a series routing configuration was selected based on manufacturing feasibility, flow predictability, modification flexibility, and overall performance. The series option also minimizes the area containing fluid routing components which reduces MMOD shielding mass. The series configuration has one inlet and outlet line, with alternating heat pipe-fluid loop interfaces going to each side of the panel set. More details about both the fluid loop routing, radiator panel, and heat pipe designs can be found in later sections. For an element operating at relatively high temperatures for spacecraft thermal control systems, thermal induced deformations across the length and width of the panel sets and array are a technical challenge. The team is considering splitting the panel faceplates into fins with each fin being connected to only one heat pipe; this presents an avenue to reduce thermal expansion effects if required.

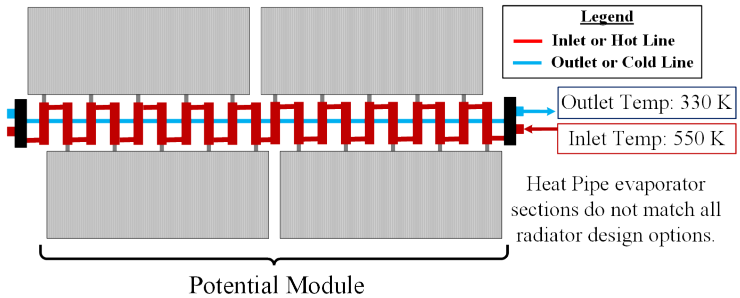

Figure 8. Potential module with fluid loop-radiator panel

This design, with the defined panel sets, was then evaluated with respect to the required total radiative surface area (800 m^2 per Brayton) to determine how many panel sets could be included in an array. Based on preliminary structural analysis, a total array length of ~20 m was selected with each of the eight panel sets providing a total of 10 m^2 (double sided) of radiative surface area (Figure 9).

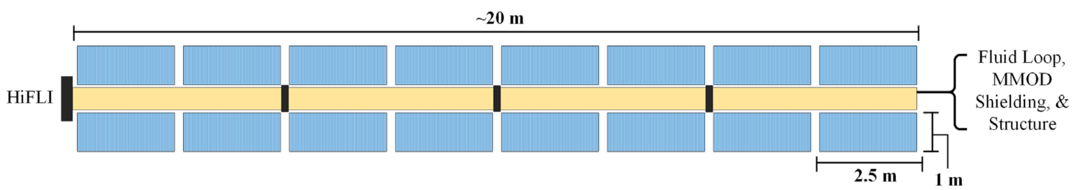

Figure 9. Eight Panel Set Array.

3. Radiator Panel Design

Through previous NASA investments, high temperature radiator panel technology was matured to TRL 6, albeit with slightly differing requirements. The NASA GRC double-sided 2nd Gen Radiator Demonstration Unit (RDU) was selected as a design baseline for the MARVL system due to its higher maturity relative to competing options [14]. The 2nd Gen RDU radiator was originally designed for lunar surface applications where performance in a partial gravity environment is applicable. This radiator design included 14 CP-Ti water-based heat pipes bonded into Pocofoam™ foam saddles, composite facesheets bonded to both sides of the heat pipes, and fluid loops with water as the working fluid. Heat transfer between the trunkline and the heat pipes occurred via annular flow sections where the trunkline fluid ran over the evaporator section of the heat pipes. Modifications in size (from 2 m x 2.7 m to 1 m x 2.5 m) and heat pipe design were necessary to meet MARVL requirements.

To achieve optimal heat transport, the MARVL heat pipe length needed to be reduced to 1.25 m long due to the target application necessitating operation in a micro-gravity environment rather than lunar gravity. Heat pipe heat transport capability is inversely proportional to length. Heat pipe count, spacing, temperature rating, and size vary between four unique panel set types as recommended by a systems analysis mass study. Some panels contain 11 heat pipes per panel while others contain seven heat pipes. This configuration allows for significant mass savings by accounting for the decrease in working fluid temperature down the length of an array.

At the time of the FPR, the team modeled radiators with four different fluid loop routing configurations (Figure 10) in TD v6.3, using FloCAD items for the fluid flow and heat pipes. From the initial four concepts illustrated in Figure 10, aspects of Concepts 1 and 2 were deemed desirable. These concepts include inlet flow paths which transport working fluid down the length of the array with a return line separately returning working fluid back to the fluid source line without interfaces to the heat pipes. Concepts 3 and 4 involve transporting inlet working fluid down one side of the panel set and rerouting that same flow back to the fluid source line with connections to the heat pipes. Concepts 3 and 4 present concerns regarding Coefficient of Thermal Expansion (CTE) mismatch as the temperature of the sides of the panel set at the root of the array will differ by 170 K. Maintaining a temperature gradient down the length of the array, in contrast to a width-based gradient, was deemed preferable. As opposed to Concept 4, the other concepts provide a central area for fluid loop routing which is more advantageous from an MMOD shielding perspective. It was determined that shielding of the fluid loops would be required not just for MMOD protection, but also to minimize the effects of changing environmental temperatures on the fluid loop temperatures, providing a more consistent input temperature for the heat pipes and thus more predictable heat rejection.

The original four fluid loop designs all included either two or four redundant fluid loop lines. However, this redundancy at the radiator array level was deemed unnecessary based on findings from a preliminary PHRS Failure Modes and Effects Analysis (FMEA) which determined that redundancy could adequately be incorporated at a higher system level; for instance, as cross strapping between Brayton engine working fluid lines. Additionally, transitioning to the series configuration facilitates a design with improved manufacturing feasibility, flow predictability, modification flexibility, MMOD shielding needs, and overall performance.

After this design was selected, a TD model of a full radiator array (Figure 9) was developed. This array model was run at the expected environmental sink temperature extremes (6 K and 290 K) and proper fluid loop inlet conditions. Since FloCAD pipes do not directly predict the pressure differential across the fluid loop, these values were obtained via a total fluid network model developed in the Generalized Fluid System Simulation Program (GFSSP). In addition, custom TD user logic was added to ensure the FloCAD heat pipe objects did not dissipate heat in excess of the dryout heat pipe transport limit. This model was used to assess the working fluid temperature delta across the array, total heat rejected, and local gradients in the radiator panel sets.

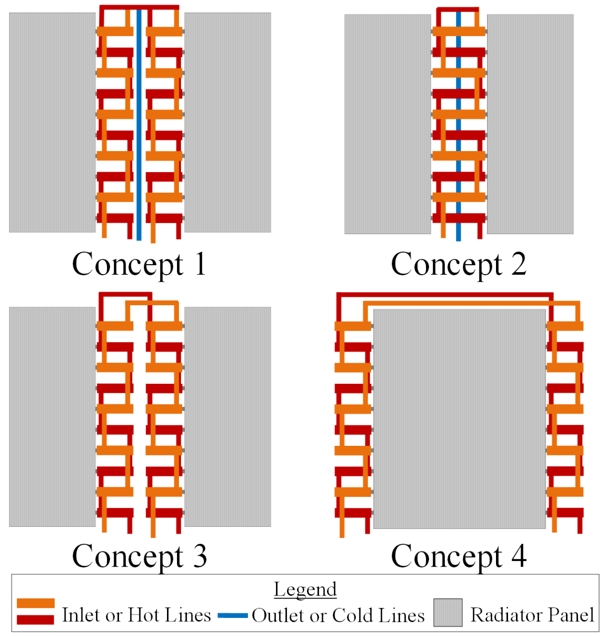

Figure 10. Four Fluid Loop Routing Options Prior to Downselection.

4. Fluid Loop Design

The flow performance for each of the concepts shown in Figure 10 were analyzed to determine what the expected pressure drop is during operation. This was accomplished first by determining the pressure drop across a single panel-set, then using that prediction to calculate the overall array pressure drop. Pressure drop values were determined through computational fluid dynamics (CFD) analysis using STAR-CCM+. Due to the complexity and amount of resources required, the CFD analysis was conducted on a single panel-set level. For array level analysis, a fluid network simulation was developed in GFSSP where single nodes represented each panel-set. The flow restriction values used for these representative nodes were calculated using the pressure drop derived from the CFD analysis.

In addition to the flow performance, the estimated mass associated with each concept was studied. Increasing fluid line sizes meant less pressure drop at the cost of increased tubing mass and NaK-78 fluid volume. If the flow could be split into two or four separate lines per panel, smaller line sizes could still be used and allow a reasonable pressure drop. However, it was quickly determined that the latter two concepts (Concept 3 and 4) were unfeasible due to the large pressure drop associated with having to route the fluid back past the entire array through the other half of a panel-set and would result in requiring very large tubes. Concepts 1 and 2 avoided this by having a slightly larger single return line traveling back to the main trunkline.

The decision between Concept 1, Concept 2, and the final downselected series configuration mentioned previously came down to the complexity in splitting up the flow. A decision was made to simplify the panel-to-panel connection to a single inflow and outflow boundary, as otherwise there would need to be a large amount of force needed to seal the interface surfaces between each panel-set; this also nullified the need to have two or four flow lines through each panel-set from a flow redundancy perspective. Through CFD analysis it was also shown that, for a single inlet and outlet, there would be difficulty in ensuring the flow split was equal through the various lines. The variation in flow was highly geometry dependent and may require active flow controls to ensure even splitting. Thus, the final downselected series concept provided the simplest solution from a flow performance perspective. It also provides the smallest tubing footprint when looking at the perspective down the length of the array; this helps to reduce losses in radiator performance by reducing the view factor between the panels and the tubing, MMOD shielding, and structure supporting the fluid loop.

The tubing material was selected to be SS 304L for its compatibility to NaK-78. Previously, CP-Ti was considered to reduce mass, but it was found that there is insufficient lifetime compatibility data for NaK-78 at the elevated temperatures in this application. Thermal deformation analyses are ongoing which are investigating the CTE mismatch between the heat pipes and fluid loops while minimizing temperature differentials between and through materials.

C. Heat Pipe Design, Analysis, and Heap Pipe-to-Fluid Loop Interface

Boyd Corporation is conducting heat pipe performance and mass analyses for titanium-water axial groove heat pipes across three diameter variants (12.7 mm [0.5 in], 19.05 mm [0.75 in], and 25.4 mm [1.0 in]) operating at maximum temperature ratings of 450 K and 550 K. The analysis incorporates Grade 2 CP-Ti material properties, a minimum wall thickness of 0.7 mm (based on the 2nd Generation RDU), extended evaporator length of 500 mm (to reduce temperature deltas), 1 m condenser length, and 0.5 kg/s NaK-78 fluid loop mass flow rate. For each heat pipe configuration, performance data is being generated including mass estimates (including water mass), heat transport versus temperature curves, change in temperature (delta-T) versus heat transport trends, and operational limit analyses (capillary, boiling, viscous, sonic, and entrainment limits). Structural integrity at the respective temperature limits is determined via hoop stress analysis considering internal fluid pressure which applies factors of safety per JSC 65828 (Structural Design Requirements and Factors of Safety for Spaceflight Hardware).

For the NaK-to-heat pipe interface, three heat exchanger concepts are under evaluation: annular, coil, and serpentine configurations. Preliminary assessments indicate the annular concept offers superior thermal performance and pressure drop characteristics while maintaining excellent mass efficiency; though it presents the most complex manufacturing challenges. Ongoing CFD analyses will optimize these concepts for low-Prandtl-number NaK flow. Ongoing assessment will evaluate thermal performance, pressure drop, and manufacturing feasibility. The heat exchanger must utilize stainless steel construction due to limited NaK-titanium compatibility data, with attachment strategies under development including tapered wedge, slide-on-and-braze, and clamp mechanisms.

D. High-Temperature Fluid Interface (HiFLI) for in-Space Assembly Process

A connector capable of holding a seal under relatively high temperature flow conditions as well as being compatible with robotic manipulation systems is required for the iSA modules for radiator installation operations. Two locations were considered for the HiFLI: (1) between the fluid loop and heat pipes and (2) between the fluid loop and main trunkline and adjacent modular radiator units (see Figure 9). As each radiator panel contains over ten heat pipes, the complexity of robotically attaching ten pipes simultaneously and ensuring reliable contact force to facilitate heat transfer was prohibitive. As such, the project focused on concepts for a connector interface that enables fluid transport from the thermal trunkline to and between radiator units.

The connector requirements include maintaining integrity under prolonged exposure to liquid NaK-78 at elevated temperatures, providing inlet and outlet fluid flow paths, minimizing fluid leakage under all operational scenarios, compatibility with robotic interaction and actuation, and connection reversibility. HiFLI is self-sealing and is launched with an internal positive pad pressure of inert gas to prevent external contamination. After robotically actuated installation operations, the inert gas is vented from the lines via the thermal trunkline. Liquid NaK-78 fluid flow is then introduced to the fluid loop via valve actuation in the thermal trunkline, which transports the fluid through the HiFLI connectors.

Preventing working fluid leakage is a key constraint for both mating and de-mating operations. When the radiator units contain working fluid, the interface needs to accommodate thermal gradients due to the proximity of hot and cold fluid loop lines. To be robotically manipulated and actuated, the interface needs elements like rigid grapple features, alignment pins, and soft capture locks, along with co-design of robotic end effectors that manipulate the radiator modules. The interface is a critical component of the PHRS and will go through multiple design cycles to ensure successful connections.

V. Conclusion

The MARVL project has served several purposes. The first is that it is an Early Career Initiative funded project that is designed to give early career researchers and engineers the opportunity to learn about project management and team leadership. It has also allowed for technology development and knowledge growth among early career engineers at several NASA centers. The primary technical goal is to design a modular radiator array system for the high-power Mars transit vehicle, while a secondary goal is to have a scalable iSA array design that can be used, with some design modifications, for different NEP vehicle power levels. By the end of the project, the team will have not only a well-defined process for technological development but also actionable recommendations for future work to enable a flight demonstration.

Appendix

Driving Technology Development Requirements

According to the TMP, "multiple published studies and subject matter expert inputs indicate the target power level for a realistic Mars mission opportunity (as a hybrid NEP/Chem) is somewhere in the range of 2 to 4 MW_e." SNP's modeling efforts show an opposition-class human Mars mission closes for a nuclear power system (excluding the electric propulsion subsystem) with an α in the range of 13 to 24 kg/kW_e. System specific mass per unit power (α, kg/kW_e), is a key measure of determining if an NEP architecture closes for a given set of mission assumptions. PHRS contribution to overall system specific mass is the MARVL Key Performance Parameter (KPP). SOA is defined here as the current value of performance based on available and comparable technology, which in this case is the ISS radiators. The term "threshold" indicates minimum desirable performance and "goal" represents an additional level of achievement enabling further capability.

Table 3. MARVL Key Performance Parameter.

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

*ISS Radiators (used as panel analogy only – deployment and trunkline similar to other published NEP concepts) at 2500m² for 2MW_e NEP [16]; † 25% α reduction [13]; ‡ 65% α reduction (hotter radiators, less required area) [13]; SoA with deployment mechanisms at an areal density of 3.5 kg/m² is 16 kg/kW_e

The values in Table 3 for PHRS contribute to overall α relay that this subsystem constitutes a large portion of the total NEP vehicle mass. When selecting PHRS designs, consideration must be given to potential impacts on the rest of the nuclear power system. Minimizing overall system α is a complex non-linear relationship between radiator area, power conversion efficiency, and heat exchanger fluid operating temperature limits (technology selection dependent). In addition to the KPP, MARVL has defined driving Technology Performance Metrics (TPM) which were originally defined in the NEP TMP and are reproduced in Table 3. Current SOA, threshold, and goal values are estimated by analysis and may require revision pending new discoveries and lessons learned from PHRS technology development.

Table 4. Technical Performance Metrics.

Title	Description	Unit	Threshold	Goal
Mass per area of panels and transport	Primary heat rejection assembly mass. Total area dictated by system optimization.	kg/m²	4.5	3
End-of-life emissivity	End-of-life IR emissivity of radiator panels. Desired solar absorptivity values dependent on vehicle orientation relative to Sun.	N/A	0.85	0.9
Lifetime	Expected mission duration with margin for a single ~2.5 year crewed mission to Mars. Goal value enables multi-mission reuse.	Years	3	10
Title	**Description**	**Unit**	**Range**	
Total power radiated (power radiated per MWe)	Encompasses a 2 to 4 MW_e system and 25 to 40% power conversion efficiency expected to minimize α balanced with limiting radiator area	MW_{th} (MW_e/MW_{th})	3 to 12 (1.5 to 3)	
Outlet temperature	Encompasses range of outlet temperature expected to minimize α balanced with limiting radiator area given possible power conversion inlet temperature (PCIT) values	Kelvin	320 to 450	
Inlet temperature	Encompasses range of inlet temperature expected to minimize α balanced with limiting radiator area given possible power conversion inlet temperature (PCIT) values	Kelvin	550 to 750	

In addition to the technical metrics in Table 4, human-rated flight requirements (including fault tolerance, redundancy, and fail-safe modes) will have a large effect on the overall PHRS design. It is expected that crew safety and system reliability will be driving requirements for a crewed Mars mission. Technology development activities for human-rated systems typically have the most difficult hurdles to clear prior to mission infusion, so early consideration of applicable flight requirements will remove barriers for future increments of technology development (e.g., ground and flight demonstrations). MARVL has derived a set of requirements from relevant Design and Construction (D&C) standards used for current human-rated spaceflight systems. Specific attention has also been given to assembly and component failure modes and life limiting mechanisms via FMEA development.

Process for Modeling Cases in Thermal Desktop

Considered in the TD model for space thermal environment analysis are orbit altitudes, orbit eccentricities, trajectories, beta angles, and hot/cold cases; this results in a total of 328 different cases. A breakdown of the modeled variables is provided in Figure 11.

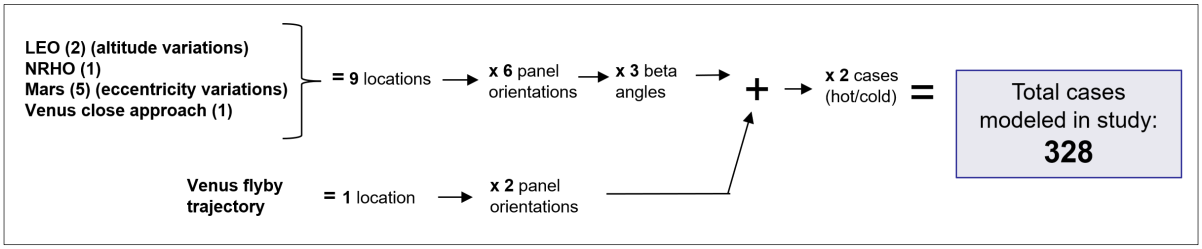

Figure 11. Summary of 328 total cases modeled in Thermal Desktop.

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