NASA/TP–20260001499

Technology Maturation Plan for High Power Nuclear Electric Propulsion

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February 2026

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National Aeronautics and
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February 2026

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NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Technology Maturation Plan for High Power Nuclear Electric Propulsion

Space Nuclear Propulsion (SNP) Project
National Aeronautics and Space Administration

16 February 2026
Document Number SNP-PLAN-0043

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Revision History

Status	Revision	Description	Effective Date
Draft	0.1	Initial draft for internal government review	13 Oct 2022
Draft	0.2	Updated draft for non-advocate and public review	22 Mar 2023
Draft	0.3	Draft responsive to NESC findings	30 Jan 2024
Baseline	1.0	Baselined version	7 May 2024
Baseline	1.1	Formatted for LaTex	16 Feb 2026

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Forward

Nuclear electric propulsion (NEP) has been considered for space exploration for over six decades. The promise of high specific impulse leading to reductions of a factor of ten or more in propellant mass has kept NEP in the mix for high Δv mission evaluation. Despite the potential advantages and significant ($1B+) investments in NEP to date, recent NASA-sponsored reviews by both the NASA Engineering and Safety Center (NESC) and the National Academies of Sciences, Engineering, and Medicine (NASEM) found that essentially all technologies for all five NEP-vehicle Critical Technology Elements (CTE – nuclear reactor, power conversion, power management and distribution, electric propulsion, and heat rejection) are at maturity levels well below those required for credible mission architecture design. Both reviews urged renewed investments in NEP technology advancement. This technology maturation plan (TMP) was developed by NASA's Space Nuclear Propulsion (SNP) project to provide a detailed roadmap in response. Major guidelines followed in the development of this TMP included:

1. Transparent assessments of both the state-of-the-art and advancement hurdles,
2. Opening of the trade space to recognize advances in relevant areas beyond those considered in previous efforts,
3. A modular, extensible "building block" approach to CTE development and demonstration,
4. Quantified advancement targets with rigorous milestone-driven schedules, and
5. Independent review of the plan, specifically focused on an evaluation of the appropriateness of rigor of the technology advancement milestones.

The first item was accomplished through a combination of broadly attended technical interchange meetings between technical community members, in-depth subject matter expert (SME) evaluations of the present state-of-the-art, and robust systems analyses to quantify the value and impact of different technology choices. For the second item, the project cast a wide net to identify and evaluate the utility and impact of technologies that had not previously been considered for the NEP application and/or that had been advanced by other projects for other purposes to the level where they could be also considered for NEP. For the third item, heavy emphasis was placed on the development and demonstration of hardware "at scale", which for a human Mars mission was determined to be demonstrations at 1 MW. For the fourth item, specific advancement goals were set based upon the definitions of each technology readiness level (TRL) and detailed advancement roadmaps were developed to show what the project would consider successful achievement of TRLs 4 and 5. For the last item, a non-advocate panel led by the NESC Propulsion Technical Fellow reviewed the TMP and advancement goals contained therein. All findings from that review have been addressed in the present document.

The technologies selected for each CTE and the specific advancement milestones in this document are based upon "best guess" SME evaluations of the current state-of-the-art, the perceived difficulty in advancing these particular options from their present status to higher TRL, and the appropriateness of these options judged relative to the goal of realizing a MW-class human Mars NEP system. While technology choices have been made in this TMP based on significant effort and evaluation of alternatives, that is not to say that other technologies could not or would not be considered for a high-power NEP system. However, for such an alternative to be considered, an offeror would be required to also propose a development plan and advancement milestones commensurate with the level of rigor and detail found in this TMP.

The development roadmaps in this TMP show a four-year path to TRL 5 for each CTE. This timeline was based on conducting a crewed Mars mission during the 2039 opposition-class opportunity – a mission timeframe used by the NESC and NASEM in those technology status reviews. SNP is fully aware that the resources needed to support the full scope of this TMP and complete all advancement in the four-year timeframe are unlikely. Consequently, many of the development efforts in this TMP are separable, so relevant incremental advancements can be accomplished in each area as funding is available.

In conclusion, the promise of NEP is unrealized after over sixty years of intermittent NASA investment, in large part due to the lack of a comprehensive, coordinated technology development roadmap. The present NEP TMP was written to fill this void, defining specific advancement milestones and leveraging non-advocate reviews to assure and objectively verify technology advancement. While there is no guarantee that projected technology capabilities will be realized or that the technology selections contained in this TMP will be the eventual options implemented for NEP, the TMP philosophy, if followed, will yield coordinated progress and provide quantitative inputs on NEP that can be used by future planners and decision makers.

Acknowledgments

The authors first want to thank the senior NASA Space Nuclear Propulsion (SNP) project personnel, Doug Burns and Adam Martin, who were essential in guiding document development and document finalization. We also want to thank past and present SNP project management, namely Jason Turpin, Rebekah Whitten, Dayna Ise, and Michael Kynard, and the NASA Space Technology Mission Directorate (STMD) Space Nuclear Technologies portfolio manager, Anthony Calomino, for their support throughout this process.

SNP was determined from the outset to develop this nuclear electric propulsion technology maturation plan (NEP TMP) in full view of the technical community, with inputs accepted from across the aerospace community to ensure that the plan was comprehensive with respect to the technology options considered. The project tapped the community for ideas and inputs and is in debt to the many individuals and organizations who provided a tremendous response in the course of this effort. Major support came from three sources:

1. The participants of the six technical interchange meetings (TIMs – one held for each CTE and one specifically directed toward in-space assembly) provided SNP with a broad-spectrum view of relevant past, present, and ongoing technology development efforts. The TIMs were overwhelmingly successful, with hundreds of technologists from relevant commercial, academic, and government organizations participating. These TIMs often resulted in followup deep dive conversations with specific organizations, providing SNP with additional insight into present efforts and potential future technology solutions. SNP wishes to thank each of the TIM participants, and while there were too many to call-out here, we do thank below the volunteer presenters from the TIMs:

   J. Laube, R. Burrell, B. Peterson (Aerospace Corp), C.R. Joyner, T. Kokan (Aerojet Rocketdyne), N. Gernert (Thermacore), J. Kesseli (Brayton Energy), D. Pounds (ThermAvant), B. Anderson, C. Tarau (Advanced Cooling Technologies), R. Scheidegger, R. Button, L. Pinero, J. Thesken, C. Hanlon, J. Csank, K. Boomer, D. Jacobson, M. Patterson, R. Edwards, S. Oleson, R. Dyson (GRC), J. Polk, G. Carr (JPL), J. Didion, J.-M. Lauenstein (GSFC), S. Rodriguez (Sandia National Labs), O. Mireles, C. Weyandt, A. Werkheiser (MSFC), W. Doggett (LaRC), R. Chambers (Lockheed Martin), D. Fischer (Astroscale), J. Schiel (Orbit Fab), J. Kugler (Redwire), I. Johnson (MAXAR), and E. Stellrecht (Moog).

2. A number of additional subject matter experts helped SNP identify key technologies of interest and the issues requiring resolution for true technology advancement. The TMP truly could not have been completed with the in-depth technical accuracy it

contains without the inputs from multiple SMEs. These include A. Krenn (KSC), A. Leary (GRC), A. Miller (ThermAvant), R. Williamson (Aerospace Corp.), S. Morrison (EPS Space), R. Hofer (JPL).

3. On 17 June 2021, SNP held a special workshop entitled “Flight Qualification Requirements for NTP- and NEP-Powered Human Mars Missions” as part of the *JANNAF Spacecraft Propulsion Subcommittee Meeting*. This workshop aimed to identify the major issues related to reliability and safety with respect to human flight and initiate a broader discussion aimed at understanding how investments in nuclear propulsion should be made to address these issues. SNP would like to thank D. Dorney (MSFC) and K. Dickens (GRC) for their roles in chairing the event and presenters S.M. Schenfeld, C.R. Joyner, and J.R. Brophy.

NESC Statement

A non-advocate review of this high-power nuclear electric propulsion (NEP) technology maturation plan (TMP) was conducted by a NASA Engineering and Safety Center (NESC) panel assembled and led by NESC Propulsion Tech Fellow in July-August of 2023. The panel included subject matter experts in nuclear systems, electric propulsion, thermal systems, and system engineering, providing a robust review of the key details required to mature this technology. The findings and recommendations of that panel were briefed to the NESC Review Board (NRB) on 17 Aug 2023, with the NRB accepting the product of the panel.

The Space Nuclear Propulsion (SNP) project proceeded to revise as appropriate the high-power NEP TMP based upon the non-advocate review panel findings. On 21 June 2024, a package describing the revisions to this TMP and providing a disposition of the NESC non-advocate review panel findings and recommendations was delivered to the NESC Propulsion Tech Fellow. The Tech Fellow accepted these revisions and dispositions as responsive to the non-advocate review panel.

Dr. Jonathan E. Jones
NASA Technical Fellow, Propulsion
17 December 2024

Executive Summary

Nuclear electric propulsion (NEP), which uses a fission reactor to power electric thrusters, has been advanced as an option to propel a human mission to Mars since the late 1950s. The high specific impulse of electric thrusters (thousands of seconds) offers the potential to significantly reduce the required propellant mass for propulsively-challenging, high Δv missions compared with thermodynamically limited conventional chemical propulsion systems that operate at up to 360-460s of specific impulse.

Projected NEP benefits have not been realized despite major NASA investments in the Space Nuclear Auxiliary Propulsion program in the 1960s, the Space Exploration Initiative in the 1990s, and Project Prometheus in the early 2000s. A critical review by the National Academies of Sciences, Engineering, and Medicine (NASEM) indicated that the core issue hindering high-power NEP has historically been the lack of coordinated research and development focused on the demonstration of technically mature (TRL 5) MWe-class hardware. This finding was reinforced in a review of nuclear propulsion technical maturity by the NASA Engineering and Safety Center (NESC), which concluded that most of the key NEP technologies are currently at or below TRL 4 at the component level and lower still at the subsystem and system levels. The NESC review further indicated that for many of the technologies the advancement degree of difficulty (AD^2) – a descriptive term to quantify the difficulty in advancing the readiness of a technology for a given application – was high enough to warrant an approach with multiple development paths to minimize the overall advancement risk.

As a response to the NASEM and NESC findings, the Space Nuclear Propulsion (SNP) project developed this focused Technology Maturation Plan (TMP) as a roadmap for the technology advancements required to support informed decisions on the efficacy of NEP systems for humanrated Mars missions in the late 2030s. This mission timeframe aligns with the NASEM baseline assumptions, and it drove the project to develop a four-year technology maturation schedule to achieve TRL 5 in the mid-to-late 2020s to support the 2030s design of NEP-propelled cargo and human missions to Mars.

The schedules in this TMP are consistent with the NASEM recommendation that:

> **"If NASA plans to apply NEP technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development"** [emphasis in original]

However, it is also understood by the project that the schedules in the TMP are extremely aggressive and that it is unlikely there will be sufficient resources available to complete the plan as written in the assumed four-year timeframe. For this reason, the development tracks and tasks within each track were developed to be separable, permitting milestone-oriented progress with the project using this document to set and adjust advancement priorities as funding becomes available. Non-advocate review (NAR) is a project cornerstone used to gauge progress at every major advancement milestone and to provide an independent assurance that technology maturation has been achieved.

Combining an NEP system with a chemical propulsion stage, called a NEP-Chem system, could be an appealing option for human Mars missions. A notional NEP-Chem vehicle is shown in Figure 1. The chemical stage using a LOX-methane engine provides the high-thrust required for fast maneuvers in planetary gravity wells, with the NEP stage providing the balance of the Δv required to complete the interplanetary transfer mission. A NEP-Chem vehicle could provide mission profiles comparable to nuclear thermal propulsion (NTP) systems (i.e., comparable trip-times and launch mass requirements) with smaller, lower-temperature reactors.

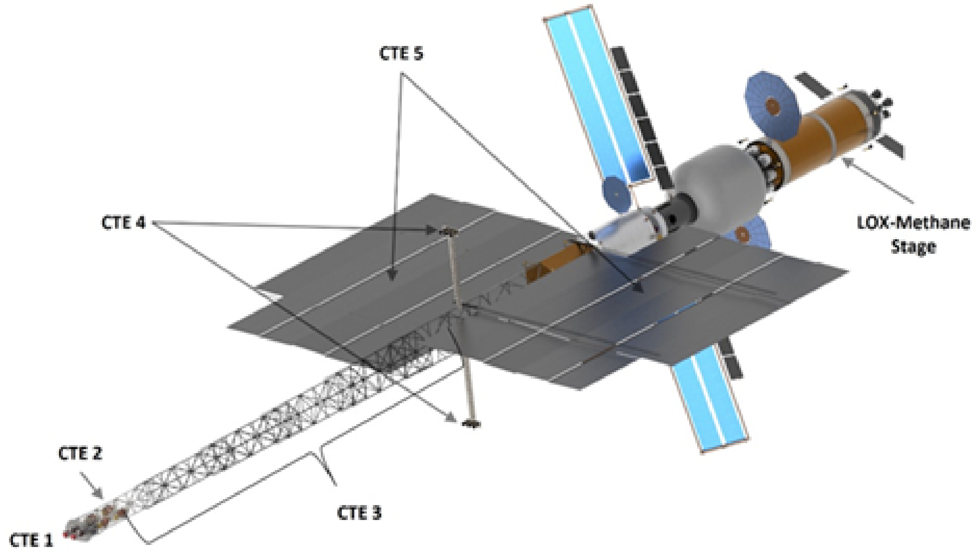


Figure 1: A Notional NEP-Chem Vehicle Showing the Five Critical Technology Elements (CTEs) of the NEP Stage

The NEP stage can be divided into five subsystems, or Critical Technology Elements (CTE):

- CTE-1: Reactor and Coolant Subsystem (RXS)
- CTE-2: Power Conversion Subsystem (PCS)
- CTE-3: Power Management and Distribution (PMAD) Subsystem
- CTE-4: Electric Propulsion Subsystem (EPS)
- CTE-5: Primary Heat Rejection Subsystem (PHRS)

Figure 2 shows a block diagram of a representative NEP system showing the relationship of the five CTEs. Note that this is a representative diagram only with the exact configuration being dependent on the specific design choices employed.

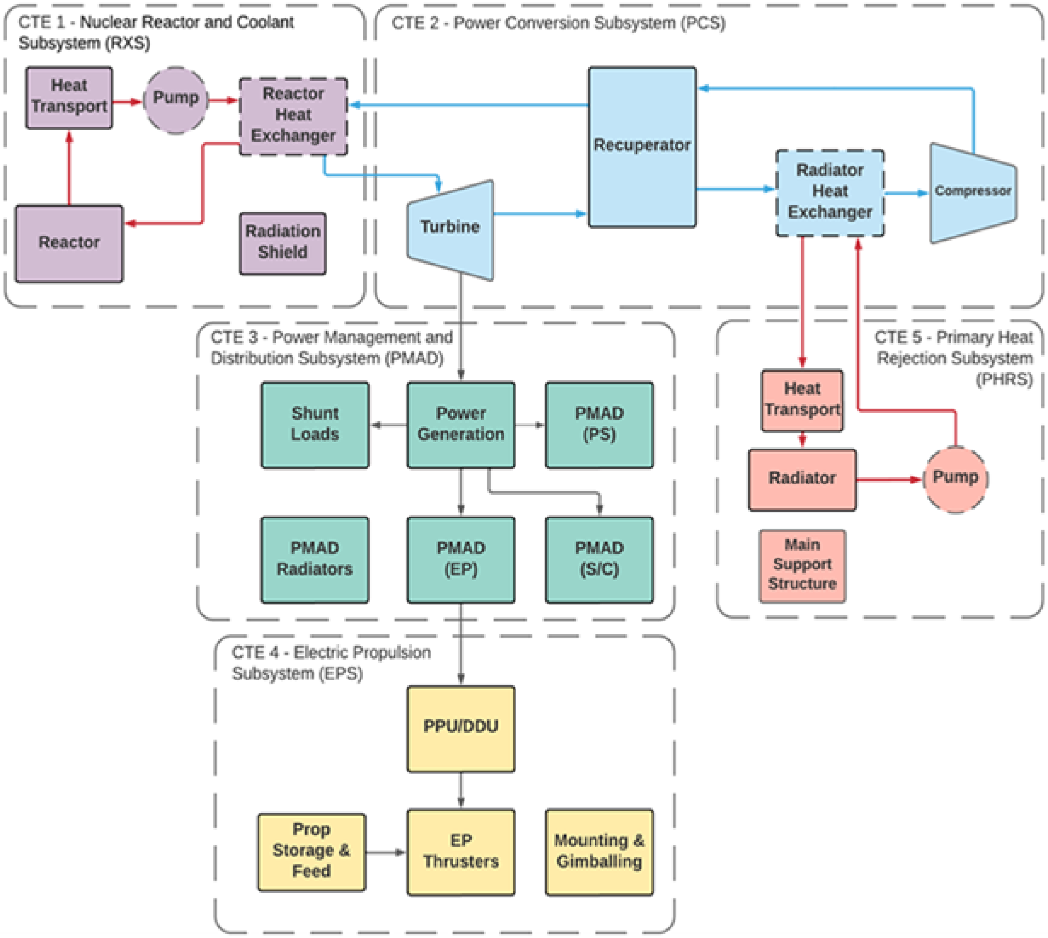


Figure 2: Block Diagram of a Representative NEP System.

Starting in Fall of 2020, the SNP project was given the task of identifying viable, high-confidence options for each CTE that could be assembled to produce a credible NEP system. To meet this goal, a thorough understanding of the tasks required to mature critical technologies was developed based on current state of the art assessments and then used to generate the CTE advancement schedules and assess advancement risks. The project identified key areas for collaboration with government and industry partners and considered execution strategies to engage those partners during the early stages of implementation, taking advantage of and, where feasible, aligning with ongoing efforts and investments.

Over the past two years, the project identified and performed a detailed assessment of the technologies available for an NEP system. This included a deep dive into the literature summarizing past NEP efforts, hosting several broadly attended technical interchange meetings focused on the various subsystems comprising an NEP system (primarily from December 2020- April 2021), and holding an even larger number of individual technical discussions with institutions, partners, and subject matter experts. The project cast a wide net to investigate available technologies, including those developed for applications outside of NEP (e.g., electric aircraft power system design, gas turbine technologies for aircraft, power generation applications, and switch designs for commercial power distribution).

There have been many architecture studies concerning the efficacy of NEP for human Mars missions. These studies yield sets of missions that ‘close’ for a given set of ground rules and assumptions. The long-standing issue with the approach is that of uncertainty in mass, lifetime, and performance estimates for MW_e-class NEP system hardware. The NASEM and NESC assessments both lead to the conclusion that these uncertainties will be large for the key NEP subsystems due to low technical maturity (low TRL and high AD^2). The relative uncertainty in architecture study outputs is highly dependent on the quality of the input technology descriptions. In addition, NEP-class mission opportunity selection has been a moving target for six decades and the propulsive requirements can be significantly affected by the selected opportunity. For this reason, the SNP project has opted to pursue a strategy that targets specific performance capabilities that enable a large fraction of potential mission opportunities. The goal of SNP is to demonstrate high power hardware in a manner sufficient to reduce existing uncertainties to a point where credible mission studies can be performed, and data-driven design and analysis can support further maturation from TRL 5 to the application of NEP on operational flight missions. While NEP technology is not yet sufficiently advanced to support detailed architecture development with high confidence, multiple published studies and subject matter expert inputs indicate that the target power level for a realistic Mars mission opportunity (as a hybrid NEP/chemical propulsion vehicle) is somewhere in the range of 2 to 4 MW_e. The 2039 opposition-class mission opportunity is propulsively intense, so development of a propulsion system that could accomplish that mission would also be enabling for a wide range of less challenging mission opportunities.

The maturation plan focuses on the development and demonstration of hardware that will provide confidence that the demonstrated NEP technologies can accomplish a wide range of missions. For this, SNP has chosen an approach that will demonstrate 1 MW_e building blocks for the key power conversion, power management and distribution, electric propulsion, and heat rejection subsystems. Validated hardware (supported by modeling and simulation sufficient to predict performance and reasonably project lifetime and reliability) is expected to be adaptable to any human-rated architecture through straightforward engineering efforts. Quantification of the key performance parameters (KPP) such as mass, performance, and reliability of MW_e-class hardware will provide the confidence required by decision-makers to move beyond TRL 5 to operational system flight hardware that can support a mission target. The modular approach provides flexibility in design to meet the mission power requirements either by (credible, data-supported) scaling of CTE power capabilities or by using multiple MW_e-class building blocks working in concert. CTE advancements will likely be out of sync in the instance where funding is not available to advance all subsystems simultaneously. This requires that the project maintain a strong systems engineering and integration posture that sets and controls the interfaces between the CTEs so technologies developed for each element will support operation of the interfacing elements.

The project has developed a set of system mass and performance models that can be coupled to a mission analysis model. These modeling capabilities were used to compare the effects of different technology choices for each CTE and to develop a set of preliminary KPPs for both the overall NEP system and for each CTE. The major system and subsystem KPP goals are shown in Table 1. Note that the term “threshold” does not indicate a boundary in the associated parameter space where the mission fails to close. Rather, these indicate the minimum KPP values that should be targeted based on SME assessments. The higher “target” values are based on more aggressive SME estimates – meeting these targets enables a given mission to close with a lower-mass vehicle architecture. Additional modeling advancements, at the CTE- and system-levels, are part of the TMP development efforts and refinements for both technology plan adjustments and mission planning are expected as the maturation process produces real data.

Table 1: Major System and Key Subsystem KPPs for a Human Mars NEP-Powered Mission

Parameter	**KPP Value**
Power system mass (kg/kW$_e$) (consists of CTEs 1, 2, 3, and 5)	24 (threshold), 13 (target)
Total electric propulsion thrust (N)	65–120
Electric propulsion efficiency and I_{sp} (s)	Efficiency and I_{sp} shown in Fig. 2.1 – dependent on system choice
Nominal mission duration (hours)	25,000
CTE-1 power output (MW$_{th}$)	5–16
CTE-1 outlet/CTE-2 inlet temp (K)	1200 (threshold), 1400 (target)
CTE-2 power output (MW$_e$)	2–4
CTE-4 thruster lifetime (hours)	27,000–32,000 (provides margin to the nominal mission, depends on thruster choice)
CTE-2 outlet / CTE-5 inlet temp (K)	550–750
CTE-5 return / CTE-2 inlet temp (K)	320–450

The nominal technologies selected in this TMP for each CTE, which were determined to be the most advanced and/or the easiest to advance for a MW$_e$-class system, are given in Table 2.

Over the past seven decades, many mission analyses have purported to demonstrate the benefits of high-power NEP systems for both human and cargo missions to Mars. These studies relied upon inputs from advocates of technology options that, in general, had not been tested at power levels even within an order of magnitude of that required for the mission, necessitating extreme extrapolation from an existing and limited sub-set of lower power data. Coincident with these mission studies were a number of intermittent technology development efforts, with investments totaling well over a billion dollars (not adjusted for inflation). Despite such investments, the lack of technology maturation on the elements required for a high-power NEP system was starkly illustrated in the above-mentioned assessments by the National Academies of Sciences, Engineering, and Medicine and the NASA Engineering and Safety Center. The technology maturation plan contained in this document is a direct response to those assessments and is designed to break the cycle of investment without demonstrable technology maturation. This is accomplished by fabricating test hardware and experimentally demonstrating the operation and performance of critical NEP elements at

Table 2: Highest-Confidence Options as Identified by the Project for each NEP CTE

CTE-1: Reactor and Coolant Subsystem (RXS)	
Fuel	UN or UO_2, with clad pellet fuel form
Moderator	YH_x and BeO, or BeO
Reactor Heat Transfer	Direct Gas Cooled with He-Xe coolant or Li Heat Pipe Cooled
CTE-2: Power Conversion Subsystem (PCS)	
Closed Brayton cycle	Recuperated (likely)
Working Fluid	Helium-Xenon (He-Xe) mixture
Inlet Temperature	1200 K (threshold) / 1400 K (target)
Power Level per Unit	500 kW$_e$ – 1 MW$_e$
Overall Vehicle Power Level	2-4 MW$_e$
CTE-3: Power Management and Distribution (PMAD) Subsystem	
AC Power Transmission	Voltage: 1 kV Frequency: 2 kHz
CTE-4: Electric Propulsion Subsystem (EPS)	
Hall Thrusters	Propellant: Xenon Power per Thruster: 100-250 kW$_e$
MPD Thrusters	Propellant: Lithium Power per Thruster: 500 kW$_e$ – 1 MW$_e$
CTE-5: Primary Heat Rejection Subsystem (PHRS)	
Pumped-Loop Thermal Trunkline	Working Fluid: Liquid Metal
Finned C–C Radiator Panels w/Embedded Heat Pipes	Working Fluid: Water and/or Alkali Metal

MW$_e$-class scales while concurrently creating the modeling and simulation capabilities necessary to predict performance and project lifetime and reliability. The major advancements of this TMP will be subjected to non-advocate review to confirm that maturation has occurred and to avoid an often-encountered situation where advocates overestimate the maturity of specific technologies.

Chapter 1

Introduction

In late fiscal year 2020, the Space Nuclear Propulsion (SNP) project began the process of formulating a strategy to support development of the technologies required for a high-power (megawatt-class) nuclear electric propulsion (NEP) system capable of performing human-scale missions (ref. [1]). Over the course of the past six decades, NASA made multiple large investments in the NEP arena. Major examples include:

Over the past six decades, NASA has made multiple large investments in NEP, including:

- The mercury-based 30 kW_e-class Rankine cycle power converter and 30 kW_e-class arcjet thrusters arcjet thruster developments that accompanied Systems for Nuclear Auxiliary Power (SNAP) program of the 1960s (refs. [2, 3, 4, 5, 6, 7, 8]),
- The power processing and thruster development efforts that both preceded and then became part of the Space Exploration Initiative (SEI) effort that was conducted in parallel with the Space reactor Prototype (SP-100) effort to develop a 100 kW_e-class NEP system in the early to mid-1990s (refs. [9, 10, 11, 12, 13, 14]),
- The Jupiter Icy Moons Orbiter (JIMO)/Project Prometheus effort in the early 2000s that targeted a 100 kW_e-class system (refs. [15, 16, 17]).

There have also been several recent architecture studies concerning human-rated Mars missions (refs. [18, 19, 20, 21, 22, 23, 24, 25, 26, 27]). The most recent of these examined opposition-class human Mars missions slated to occur in the late 2030s timeframe. The mission architecture for these studies assumed a hybrid NEP/chemical-propelled vehicle (NEP/Chem) that used the high specific impulse (I_{sp}) NEP-system for the interplanetary cruise phase and a liquid oxygen (LOx)-liquid methane high thrust chemical stage (two 110 kN (25 klb_f) thrust, 360 s I_{sp} engines) for maneuvers entering and exiting gravity wells. The use of a high thrust chemical system in combination with the NEP system enables a reduction in required NEP power while still achieving reasonable human-transfer trip times. Trajectory analyses performed in this study showed that such a mission could be performed with 2-6 MW_e processed through the electric propulsion system (operating for 20,000+ hours), with the large range representing different opposition-class Mars mission opportunities and permutations on the trajectory design, concept of operations, and various technology choices in the implementation of the NEP system.

Despite these efforts, two recent, independent reviews found that essentially all the major NEP subsystems needed for a human-rated Mars mission are well-below the stage of technology readiness required to make informed technology down-selections. In 2020, the NASA Engineering and Safety Center (NESC) performed a study to evaluate the maturity of the different technologies required for nuclear propulsion systems (ref. [28]). The executive summary of this report provided the following top-level conclusions regarding NEP:

- "The majority of critical technologies for… NEP/Chem… systems are relatively immature"
- "TRLs [technology readiness levels] in the literature are often overestimated"
- "The majority of critical technologies… for NEP/Chem… systems are at a relatively high level of advancement degree of difficulty (AD^2) $>$ 4 for maturation, requiring a dual development approach"
- "The proper assessment of baseline TRL and AD^2 values and the estimation of requirements and resources required for advancement have been consistent issues for NEP,"
- "Non-advocate reviews should occur at the start of a technology program and at all key milestones."

The review panel assessed a majority of candidate NEP component and subsystem-level technologies as having Technology Readiness Levels (TRLs) of 4 or below (with even lower values at the integrated system level) and stated that most had AD^2 ratings high enough to suggest that a project should pursue parallel technology research and development efforts on most critical elements of an NEP system.

In 2021, a panel of the National Academies of Science, Engineering, and Medicine (NASEM) issued a report (ref. [29]) identifying the "primary technical and programmatic challenges, merits, and risks for maturing space nuclear propulsion technologies of interest to a future human Mars exploration mission." That report contained several important findings, including:

- "Developing a MW_e-class NEP system for the baseline mission would require increasing power by orders of magnitude relative to NEP system flight- or ground-based technology demonstrations completed to date."
- "Subscale in-space flight testing of NEP systems cannot address many of the risks and potential failure modes associated with the baseline mission NEP system. With sufficient M&S [modeling & simulation] and ground testing, **including modular subsystem tests at full scale and power**, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars. Fully integrated ground testing may not be required." [emphasis added]
- "As a result of low and intermittent investment over the past several decades, it is unclear if even an aggressive program would be able to develop an NEP system capable of executing the baseline mission in 2039."

The last finding was accompanied by a recommendation that:

> “NASA should invigorate technology development associated with the fundamental nuclear electric propulsion (NEP) challenge, which is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission. In addition, NASA should put in place plans for (1) demonstrating the operational reliability of an integrated NEP system over its multiyear lifetime and (2) developing a large-scale chemical propulsion system that is compatible with NEP.”

Both reviews recommend research and development programs focused on technology advancement efforts that would support a data-driven selection of the technologies that should be used in an NEP system. The Space Nuclear Propulsion (SNP) project used these findings as guidance in:

- Identifying the most likely candidate technologies for an NEP system based on quantitative and qualitative assessments of the present developmental status and the potential impacts of various technology options on the overall system, and
- Developing a plan to mature candidate technologies to TRL/AD^2 levels that permit reliable assessments of the effects each technology choice would have on an integrated NEP system and any NEP powered mission. [emphasis added]

Based on these findings, the SNP project has formulated a technology maturation strategy that will realize TRL advancement through milestone-based hardware development and testing supported by modeling and simulation activities. The project aims to perform work with hardware tested at the sizes and scales necessary to bring all key NEP technologies to readiness levels where they can be credibly considered for use in completing a range of human Mars missions. The goals of the modeling and simulation efforts are to demonstrate understanding of the important and controlling physical phenomena at various levels of hardware scaling and integration, from the component level to the overall integrated system, and to aid in the prediction of lifetime capability and life-limiting mechanisms for a full-scale, full-duration mission.

The SNP project NEP technology maturation plan (TMP) is not based upon a specific fixed-point mission architecture or vehicle design. Dating back to the late 1950s there have been scores of architecture studies related to the efficacy of NEP, including, for example, SEI, JIMO/Project Prometheus, and the recent tranche of studies referenced above. These studies yield sets of missions that ‘close’ for a given set of ground rules and assumptions, but the long-standing issue with this approach is that the uncertainties regarding inputs on mass and performance for a MW$_e$-class NEP system are quite large because most of the key subsystems are still at a low TRL and high AD^2. In addition, NEP-class mission opportunity selection has been a moving target for six decades and the propulsive requirements can be significantly affected by the chosen opportunity. For this reason, the SNP project has opted to pursue a strategy that targets specific performance capabilities that enable a large fraction of potential mission opportunities.

Despite uncertainties in the results of various mission studies, we can use the general results of those studies in setting goals for the project. Specifically, the required power for an electric propulsion system on an opposition-class human-rated Mars mission for the 2039 mission opportunity, when used in combination with a chemical system, is between 2 and 6 MW*e*. (refs. [19, 21, 22, 23]) The 2039 opportunity is propulsively intense, so development of a propulsion system that could meet the requirements for that mission should also be enabling for a wide range of less intense mission opportunities. The intent of SNP is to focus on the development and demonstration of hardware that will provide confidence in and advance the readiness of NEP technologies that can accomplish this wide range of missions. To achieve this, SNP has chosen an approach that will demonstrate by test a 1 MW*e* building block for the key power conversion, power management and distribution, and electric propulsion subsystems. Hardware matured through this approach (supported by significant modeling and simulation activities) is expected to be adaptable to any human-rated Mars mission architecture once a mission target is selected. That is, successful execution of the SNP TMP will enable the flexibility to address final mission power requirements through straightforward engineering efforts accomplished either by scaling the power that can be processed by each subsystem or by using multiple MW*e*-class building blocks working in concert. In addition, developing a capability at the 1 MW*e*-level gives significant latitude to add design redundancy or spare units for each subsystem in an eventual flight design.

Over the past three years, the project performed a detailed assessment of the technologies available for an NEP system. This included a deep dive into the literature summarizing past NEP efforts, the hosting of several technical interchange meetings focused on the various subsystems comprising an NEP system [primarily from December 2020–April 2021 (ref. [30])], and an even larger number of individual technical discussions with institutions, partners, and subject matter experts. The project cast a wide net to investigate available technologies, including those developed for applications outside of NEP (e.g., electric aircraft propulsion, gas turbine technologies for aircraft and power generation applications).

Based on this assessment process, the project has focused on the ‘most likely’ technologies for each NEP subsystem, with ‘most likely’ being a qualitative evaluation weighing several factors. These include, for example, the relative maturity of the system at the size and power scales of interest, successes and difficulties encountered in past development efforts, likely scalability to the range of interest for NEP systems, the ability to ground-test units at scales of interest (either as a subsystem or as part of a larger, integrated system), and a general judgment by SNP-selected subject matter experts (SMEs) on the ability of the selected technologies to meet project-specified system and subsystem key performance parameters (KPPs).

In addition to lessons learned from past efforts that are well documented in the references, the NEP technology maturation efforts under the SNP project rely on:

- Subject Matter Expert (SME)-driven identification of technologies of interest and status quantification,
- Methodical technology development that employs hardware-based technology maturation aimed at meeting quantified advancement milestones,
- Architectural modeling that uses data obtained through the hardware-based technology

maturation effort as inputs in evaluating system-level impacts of competing technologies and assessing the implications of technological uncertainty,

- Modeling and simulation (M&S) efforts that support technology development/integration/life projection and that exposes the critical controlling parameters for each subsystem and for the overall system, and
- Non-Advocate Reviews (NARs) at key milestones to assure technology advancement has occurred.

The present document represents a comprehensive TMP written to guide advancement of NEP technology readiness to the point where it can be considered as a realistic near-term option for flight applications. As the readiness level increases, more credible systems-level impact assessments and architectural analyses can be performed to determine the effects different technology options have on the overall performance of an NEP system and to give a higher-fidelity basis for comparisons between NEP-powered systems and alternative propulsion options.

The use of objective SME-generated performance metrics is a key part of the SNP development strategy (ref. [1]) specifically noted that TRLs are often overestimated in the literature. The SNP plan emphasizes non-advocate evaluation at key project decision points to avoid the flawed analysis results and decision-making that the overestimation of TRL assures. It is noted here that TRL and AD^2 definitions are often considered to be “in the eye of the beholder.” For that reason, the SNP project has set specific quantitative metrics, the meeting of which will be accepted as conclusive evidence that TRL advancement has been achieved. Several relevant references on technology advancement executed for systems of various sizes and scales provided relevant background and guidance in the development of the present NEP assessment. These examples included a stepwise process for TRL assessment that is an Agency best practice (ref. [31]), an in-depth assessment of TRLs and figures-of-merit (FOM) as they apply to the readiness of propulsion systems for microsatellites (ref. [32]), and the assessment and management of identified risks (refs. [33, 34, 35]).

1.1 NEP Critical Technology Elements

In general, an NEP system can be subdivided into five top-level subsystems or critical technology elements (CTEs). These are given in schematic form in Figure 1.1, which shows how power (thermal, mechanical, or electric) moves between the various CTEs. The schematic is somewhat general, and some of the items in the figure are given with dashed lines signifying that those elements may or may not be present in an eventual system, depending upon the specific design configuration. As the design and development process progresses, the FOMs evaluated for each CTE are expected to include performance, manufacturability, lifetime, reliability, and contribution to the specific mass (α) of the overall NEP system.

The CTEs can be subdivided into major assemblies (MAs). MA examples include individual Brayton rotating units, thruster units, power processing units, etc. These MAs are further subdivided into components (e.g., fuel, moderator, cathode, radiator panel), which are themselves comprised of parts. The large dashed-line boxes in Figure 1.1 encloses the

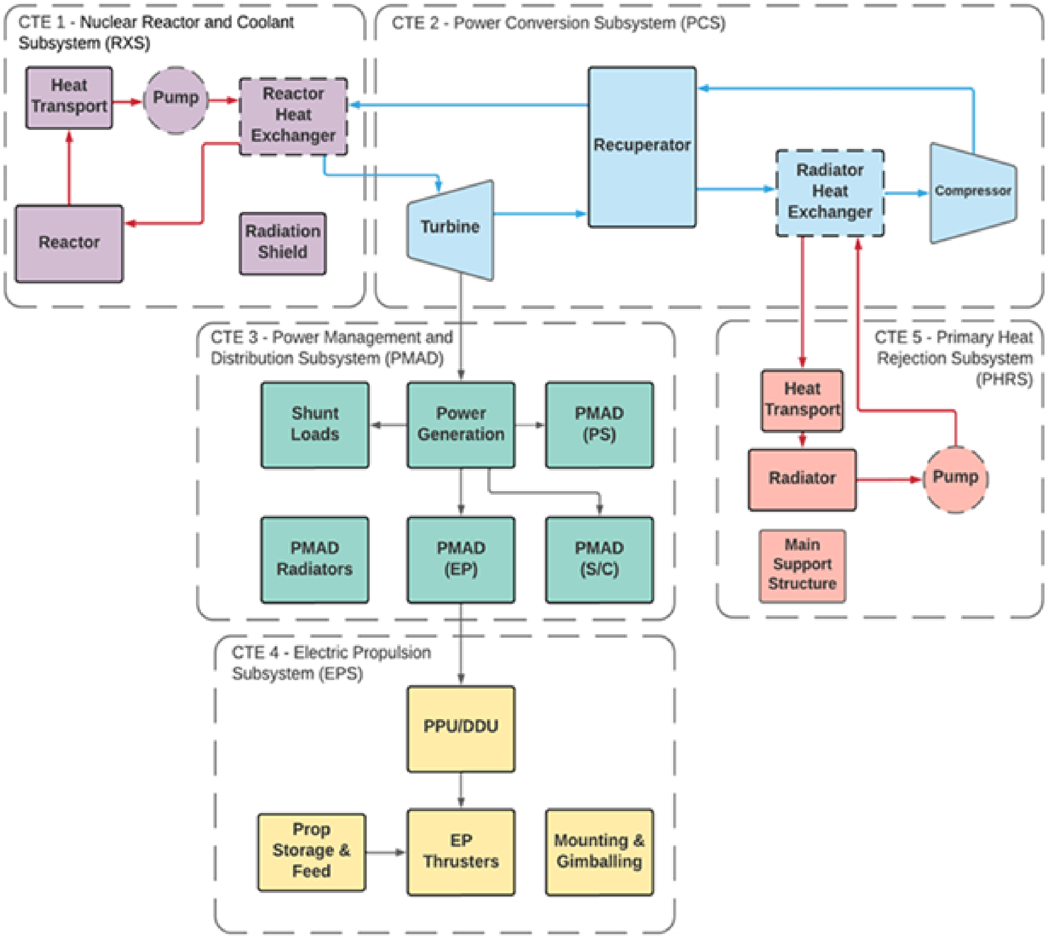


Figure 1.1: Schematic Diagram of the Critical Technology Elements (CTEs) Comprising an NEP System, Assuming the Power Conversion Subsystem (CTE-2) is a Closed Brayton Cycle System.

engineering subsystem associated with each CTE. The SNP project is focused on the advancement of the technologies that comprise these CTEs in the context of optimization of performance and mass at the overall integrated system level. Brief, high-level descriptions of each CTE follow in the remainder of this section, with detailed descriptions and full technology advancement plans for each CTE provided in the balance of this document.

CTE-1: The nuclear reactor and coolant subsystem (RXS) is the thermal power source, using high-assay low enriched uranium (HALEU, $< 20\%$ enrichment) as the nuclear fuel. The internal reactor radiation shielding is included in this CTE. The reactor subsystem generates the heat required for conversion to mechanical power by the power conversion subsystem (CTE-2). The major areas of technology advancement in this CTE concern better quantification of the fuel and moderator material properties, development of thermal management and heat transfer methods, and the implementation of lightweight reactor shielding. Multiple fuel/moderator combinations are being considered and SNP has used a tailored Analytic Hierarchy Process (AHP) (refs. [36, 37]) to generate FOMs and identify the combinations mostly likely to meet KPPs for the reactor and overall NEP system.

As an example, an early AHP exercise examined multiple fuel and thermal management options for CTE-1. Heat transfer options under consideration included 1) direct gas cooling, where a common fluid loop flows through both the nuclear reactor (CTE-1) and the power conversion subsystem (CTE-2), 2) a loop with pumped liquid lithium flowing through the reactor, and 3) heat pipes (HPs) carrying thermal power out of the reactor. Options 2 and 3 require a heat exchanger at the CTE-1/CTE-2 interface. The AHP sorting process was performed in early 2021 and applied to these reactor design options while also considering the use of different fuel and moderator options for the reactor core. Preliminary results showed that readily available fuel and moderator technologies, i.e., uranium oxide (UO_2) HALEU fuel pellets and a beryllium (Be)-based moderator, may be sufficient when employing the HP option (ref. [37]). Over the course of the project, it is expected that multiple SME-based AHP exercises will be employed to evaluate relevant technology options and permutations for all CTEs.

CTE-2: The power conversion subsystem (PCS) in the dynamic power conversion case converts the heat from CTE-1 into mechanical power that is used to turn an electric power generator that is a part of CTE-3. Numerous dynamic cycle conversion concepts (Stirling, Rankine, Brayton) have been considered for decades. As an alternative to dynamic power conversion, solid-state systems use either thermoelectric or thermionic elements to directly convert heat into electricity without the need for moving parts. A distillation of the extensive work performed to date has led to a SME-recommended down-selection to a power conversion subsystem based upon a closed Brayton cycle power conversion subsystem. Each individual power conversion unit in the subsystem is expected to support electrical power generation at levels between 0.5 and 1.0 MW_e, with the final selection being dependent on integrated system optimization. It is not anticipated that the final power rating per unit across the range will greatly impact the technology advancement process. Key technology advancement areas include turbomachinery design and materials selection, long life sealing, and (as required) heat exchanger and recuperator design and performance.

CTE-3: The power management and distribution (PMAD) subsystem incorporates all the components necessary to generate power from the dynamic power conversion subsystem comprising CTE-2 and then transmit that power at high-frequency to the electric propulsion subsystem (CTE-4) and other elements of the spacecraft requiring power. Key technologies of interest include conductors, switches, fuses, transformers, electrical isolation components, thermal control, power generator, and the means to potentially combine and isolate power inputs and outputs for the purposes of fault-tolerant operation. The PMAD subsystem design goal is to develop the lightest practical system using radiation-tolerant electrical components that either presently exist or that can be developed within a reasonable timeframe to transmit high-frequency, alternating current (AC) power at the MW_e level for on order of 20-25 khours with a very low probability of failure and/or a robust configuration that is fault tolerant and possesses recovery capability.

CTE-4: The electric propulsion subsystem (EPS) is composed of the thruster and thruster mounting assemblies, the power processing unit (PPU) assembly that is the primary thruster control system, converting the power the EPS receives to the current and voltage required by the thrusters, and the propellant tankage and delivery assemblies. If the PMAD bus voltage is approximately equal to the voltage required by the thruster, the latter could be powered directly from the bus and controlled using a direct-drive unit (DDU) instead of a traditional PPU. Both the xenon (Xe)-fed Hall and Li-fed magnetoplasmadynamic (MPD) thrusters have been identified as the most likely options for a high-power NEP system. For the Hall thruster assembly, advancement efforts focus on thruster sizing and materials, critical long-life components (e.g., high voltage radiation tolerant PPU/DDU components, high current long-lifetime cathodes, very large volume high pressure or cryogenic Xe storage), power processing/direct drive system design and fabrication, experimental and modeling assessments of interactions between thrusters in a multi-thruster 'pod' that can collectively operate at 1 $\mathrm{MW_e}$, and critical questions about the usefulness of in-vacuum ground test data in quantifying in-space performance. For the MPD thruster assembly, planned research and development focuses on achieving an acceptable level of performance while demonstrating key component (cathode) lifetime, stable thruster operation (anode attachment quality), the capability to deliver liquid Li propellant to the thruster in a controlled manner, and the development and testing of the components required to scale a high-current PPU architecture to the size and throughput levels required for a 1 $\mathrm{MW_e}$ system.

CTE-5: The primary heat rejection subsystem (PHRS) is composed of the radiators, heat exchangers, and thermal transport means necessary to reject the waste heat from the power conversion cycle to space. Radiators capable of rejecting heat loads for $\mathrm{MW_e}$-class power generation can lead to CTE-5 being the largest and most massive of the NEP subsystems. SME analysis indicates that the radiator structure will likely be based on embedded pile-in carbon composite fin technology, and that focused research and development on the heat transfer technologies for these systems are required. Both pumped-loop and passive thermal transport designs are under consideration, with a possible outcome being a pumped-loop trunk line distributing heat through heat exchangers to passive components that deliver heat to the radiator fins. Key areas of work include assuring there is effective heat spreading over the radiator surface and evaluating the capability and performance improvements that may be realized using high-emissivity coatings.

1.2 Key Performance Parameters (KPPs)

Modeling the power flow in the NEP system and the mass associated with those components comprising each CTE, coupled with a mission model have allowed the project to set initial KPPs for the overall system and for each subsystem (refs. [19, 21, 22, 23]). A few of the major KPPs for the overall system are given in Table 1.1. Mission and system modeling (for the assumed system performance and component masses of the study) have shown that an opposition-class human Mars mission will close for an end-to-end nuclear power system (CTEs 1, 2, 3, and 5) possessing an α in the range of 13-24 $\mathrm{kg/kW_e}$ and a nominal electrical power output of 2 $\mathrm{MW_e}$ (ref. [21]). The "Threshold" values shown in Table 1.1 represent those values sufficient to make NEP a credible propulsion alternative for crewed Mars missions given the resulting vehicle architecture mass. The "Target" values in the table are associated with higher performance technologies that enable a lower-mass vehicle architecture.

Table 1.1: Major System and Key Subsystem KPPs for a Human Mars NEP-Powered Mission.

Parameter	**KPP Value**
Power system mass (kg/kW$_e$) (consists of CTEs 1, 2, 3, and 5)	24 (threshold), 13 (target)
Total electric propulsion thrust (N)	65–120
Electric propulsion efficiency and I_{sp} (s)	Efficiency and I_{sp} shown in Fig. 2.1 – dependent on system choice
Nominal mission duration (hours)	25,000
CTE-1 power output (MW$_{\text{th}}$)	5–16
CTE-1 outlet/CTE-2 inlet temp (K)	1200 (threshold), 1400 (target)
CTE-2 power output (MW$_e$)	2–4
CTE-4 thruster lifetime (hours)	27,000–32,000 (provides margin to the nominal mission, depends on thruster choice)
CTE-2 outlet / CTE-5 inlet temp (K)	550–750
CTE-5 return / CTE-2 inlet temp (K)	320–450

1.3 Technology Maturation Definitions

In discussing the SNP NEP technology maturation philosophy, it is useful to introduce a few concepts. One is technology readiness level (TRL), which is a static descriptor of a technology's status. This descriptor (ranging from 1-9, with larger values assigned to more mature or 'ready' technologies) gives a quantified readiness based on NASA document NPR 7123.1, Appendix E (ref. [38]). The goal of a technology maturation plan is to raise the TRL of a system through focused development. Definitions for TRLs 2-6 are given in Table 1.2. This is the range of highest relevance because all the critical technologies under consideration for the NEP application fall at the lower end of this range, and it is the initial goal of the NEP TMP to raise those levels to TRL 5.

Table 1.2: Definitions for Technology Readiness Levels (TRLs) from 2 to 6, as given in ref. [38].

TRL	Definition	Hardware Definition	Exit Criteria
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental proof-of-concept of critical function and/or characteristics.	Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment.
5	Component and/or brassboard validation in relevant environment.	A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases.
6	System/subsystem model or prototype demonstration in a relevant environment.	A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.	Documented test performance demonstrating agreement with analytical predictions.

The AD^2 can also be used to assess technology maturity (refs. [39, 40]). This term is a dynamic descriptor designed to provide insight into the effort required to move a system, subsystem, or component from one TRL to the next. It is a measure to be used in conjunction with TRL to understand the present state of readiness of a technology, quantify the difficulty in further advancing that technology for a given application, and the likelihood that the advancement effort will be successful. The definitions of AD^2 are given in Table 1.3, with lower values being easier to advance and less risky for a project. During a technology maturation effort, a reduction of the AD^2 for a technology will accompany successful TRL advancement for that technology.

The definitions in Table 1.2 and Table 1.3 are helpful guidelines for quantifying technology status and the degree of difficulty for advancement. By evaluating technologies using NASA best practices (ref. [31]), competing technologies can be compared relative to their ability to achieve the applicable KPPs to support technically sound decision-making. While the definitions of TRL are useful in qualitatively understanding technology readiness, the project has set specific quantitative metrics that will be used as the means to conclusively demonstrate that TRL advancement has occurred. Those specific criteria as developed for SNP will be discussed in the next section.

Extensive SNP-supported, SME-based technology reviews combined with inputs from external sources and contributors indicate that, at present, no CTE-level subsystems have achieved a TRL/AD^2 required to support a detailed preliminary design review (PDR) fidelity NEP system design (typically TRL 6 with AD^2 ≤ 2 for operational missions and TRL 5 with AD^2 ≤ 3 for technology demonstration missions). In fact, most NEP technologies are significantly below this level - an SNP finding fully-consistent with the previous NESC (ref. [28]) and National Academies (ref. [29]) study findings.

Across all five CTEs, parallel development paths may be pursued at the major assembly and component level when warranted by their AD^2-values. The project determined that the AD^2 values for CTE-1 and CTE-4 (RXS and EPS) are at a high-enough level where it is prudent to pursue parallel-track technology development at the CTE-level. Only one major track is being pursued for CTE-2 (PCS), as SMEs arrived at an overwhelming consensus that a closed Brayton cycle PCS is the only viable option given the power level and the development schedule. However, two possible working fluids were initially considered for the PCS, a helium-xenon mixture and supercritical carbon dioxide (He-Xe and super-critical carbon dioxide (sCO$_2$), respectively). System modeling (ref. [41]) conducted in 2022 supported a down-selection to the He-Xe working fluid, which obviated development of the sCO$_2$ option and saved the project both significant time and expense.

The goal of the SNP NEP technology maturation plan is to increase the TRL of each CTE and reduce the corresponding AD^2 to support down-select decisions between parallel technology development paths for each CTE.

As with all complex systems, understanding and managing the interfaces between CTEs is critical to the development of an operational system. Under this NEP TMP, each interface is carefully defined by SMEs to assure that the technology decisions and specified milestones lead to subsystems that will be compatible when integrated at the system level. SNP will manage these internal interfaces to assure that individual CTE developments do not result in subsystems that are incompatible or inconsistent with the system-level requirements.

1.4 NEP Maturation Project Management

A top-level generic schedule for NEP technology development and maturation is presented in Figure 1.2. In this, there is a short phase (labeled 'project start') where initial technology assessments are finalized, candidate technologies for advancement are selected, and early development efforts that are either low-risk or high payoff are executed. The completion and baselining of this TMP falls within this phase of the schedule and represents the culmination of several tasks in this phase. During this phase, SNP will follow the NASA technology assessment process (TAP) described in ref. [42]. The TAP requires a baseline technology maturity assessment for TRL followed by an assessment of AD^2 prior to finalization of the TMP.

The selected technologies are then subjected to focused development and maturation activities in the next phase (labeled 'Maturation to TRL 4/AD^2 3'). This phase is approximately three years long, with tasks aimed at executing relevant-scale tests at the breadboard (BB) level and providing data that inform and validate models of each subsystem. In the following phase (labeled 'Maturation to TRL 5'), relevant-scale hardware-focused maturation efforts supported by modeling and simulation activities continue at the brassboard (BrB) fidelity level. During the maturation process, down-selects between various NEP subsystem technology options can occur whenever sufficient data exist to reasonably assure that technology maturation will successfully result in a system that can support flight missions. Finally, as the maturation to TRL 5 is nearing completion, efforts can start on further maturation to TRL 6 in advance of a Preliminary Design Review (PDR) for a flight mission.

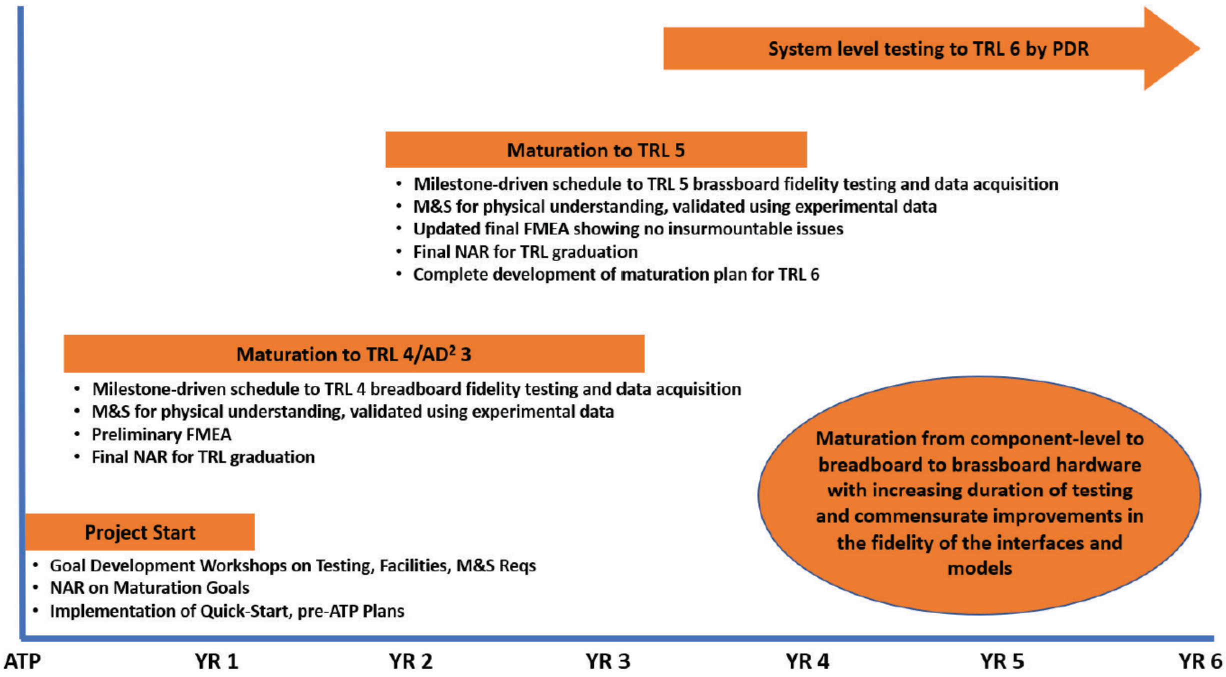


Figure 1.2: Generic SNP NEP Maturation Schedule based on achieving TRL 5 in YR 4 and maturing towards TRL 6 beyond that in advance of a spacecraft PDR.

In keeping with standard NASA engineering practices to aid with project management, shown in Figure 1.3 is an NEP technology maturation work breakdown structure (WBS). [43] In this WBS, each CTE is represented as a top-line element, with each element containing several sub-elements. An additional WBS (6.0) has been added to this figure to represent modeling and simulation at the overall NEP system level. This integrated system modeling is in addition to and partially fed by the results of detailed CTE-specific modeling and simulation activities within each major WBS element. The balance of this TMP will expand upon the generic schedule and top-level WBS, adding CTE and technology selection-specific details to the development and maturation plans in each section.

It should be noted that while the SNP project has made specific technology selections for each CTE and developed this TMP based upon those choices, the project does not rule out additional options that may be able to meet the system performance targets and developmental timelines presented. However, for any proposed technology options that are not selected in the baseline TMP, those proposing the technology are expected to offer a maturation plan and schedule that is in-line with what is presented for the technologies covered in this document. If offerors propose to investigate technologies not specifically described in this TMP, the SNP project will expect those offerors to provide a detailed TMP for their choices (similar in both scope and rigor to the developmental plans presented herein). It should further be expected that these offeror-developed TMPs would, during the course of proposal evaluation, be subjected to NAR.

Table 1.3: Definitions for the Levels of AD^2 from refs. [39, 40].

AD^2	**Definition**	**Risk**	**Comment**
1	Exists with no or only minor modifications being required. A single development approach is adequate.	0%	
2	Exists but requires major modifications. A single development approach is adequate.	10%	
3	Requires new development well within the experience base. A single development approach is adequate.	20%	
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%	Well understood (variation)
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%	Known unknowns
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. Desired performance can be achieved in subsequent block upgrades with high confidence.	50%	
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%	
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be prepared.	80%	Unknown unknowns
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	100%	Almost nothing known

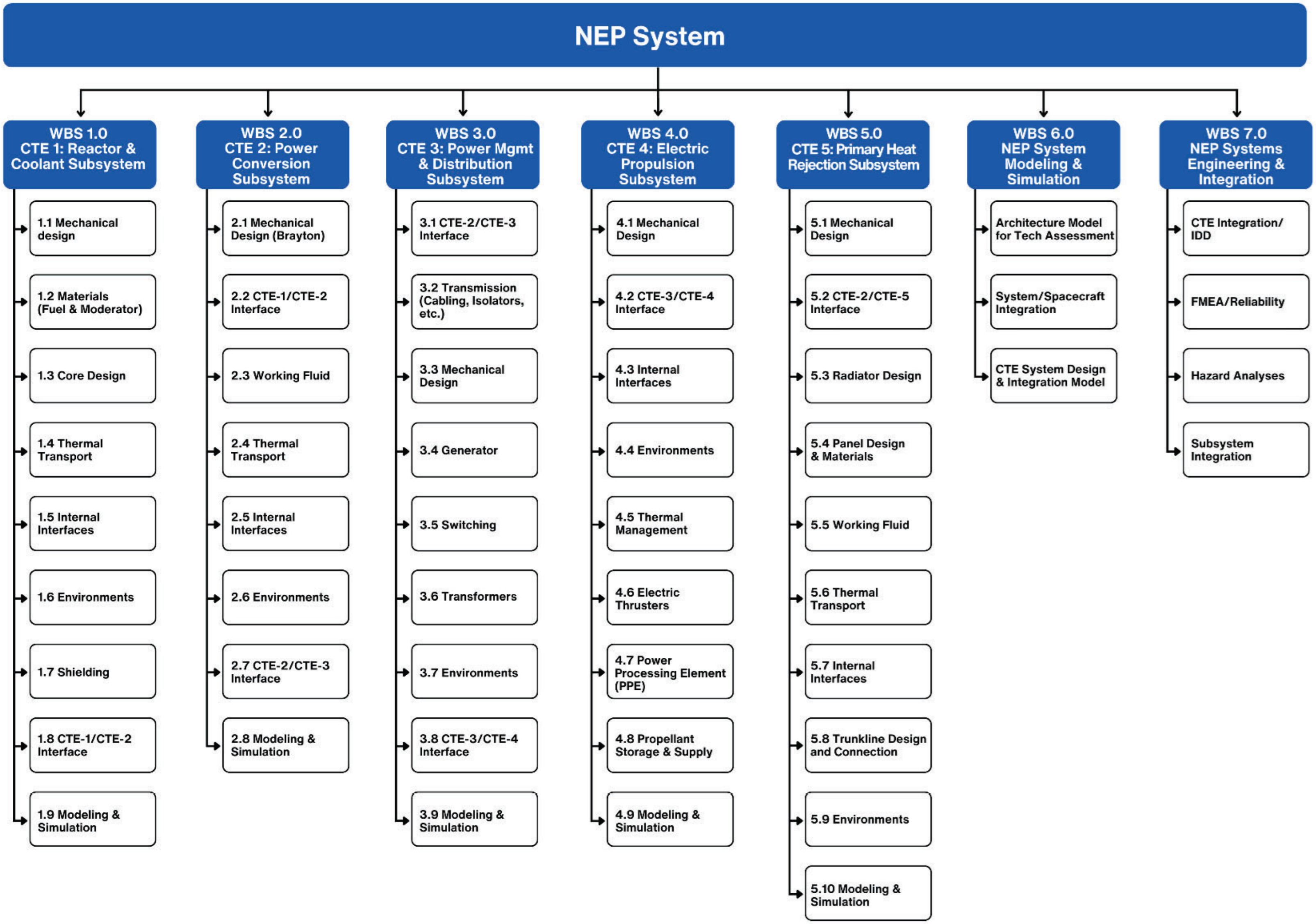


Figure 1.3: SNP NEP Work Breakdown Structure for Analysis and Project Management.

1.5 Systems Engineering and Integration Strategy

At the outset of the TMP development effort, SNP recognized that none of the individual Critical Technology Elements (CTE) were mature enough to baseline in the design of a NEP-based spacecraft with confidence and that doing so might preclude technology paths of value. Further, selection of a specific architecture, commonly referred to as a Design Reference Mission (DRM), forces ground rules and assumptions on architectural elements that are unnecessarily restrictive. For example, the assumption that the entire spacecraft must fit under a single launch vehicle shroud forces spacecraft design and technology selections that may be either practically impossible given a rational evaluation of technology development risks or non-optimal given the rapid advancements being made in key areas such as launch vehicle capabilities and in-space assembly. Based on these considerations, a strictly enforced systems engineering and integration (SE&I) approach with specific technology selections and restrictive control documents is not deemed advisable at this point. This does not obviate the need for a quality SE&I component that will 1) guide development of Key Performance Parameters (KPP) for individual technologies, 2) quantitatively evaluate impacts of proposed technology investments on the system level, 3) optimize architectural implementation strategies as technical advances are realized, and 4) assure seamless integration of the five Critical Technology Elements (CTE) once a spacecraft design is chosen. SNP's SE&I strategy to guide both initial and continuing technology development activities rests on a robust, flexible, probabilistic modeling and simulation system for initial development and continuing refinement of the KPPs, continuing SME evaluations of technology options and progress, and SNP-level configuration control with non-advocate review at critical junctures.

The required comprehensive modeling and simulation capability is in place and described in detail in Chapter 2 of this document. This was used, with SME inputs, to derive the Threshold and Target KPPs shown in each of the CTE development descriptions in Chapters 3 through 7. The model is modular with respect to the CTEs to allow different technology options to be simulated and traded to ensure that the overall system is feasible (power balance closure) and that mission performance requirements can be met. Exemplary system configurations were developed, and extensive parametric analyses were performed to quantify anticipated system performance space based on “best available” technology capability estimates for each CTE. For validation and to select initial KPPs as starting points for optimization, an opposition-class mission with crewed launch in 2039 was evaluated. This architecture is sufficiently difficult to bound all reasonable conjunction-and opposition-class missions in the 2040 timeframe. The architecture and technologies chosen were generally consistent with those used in recent “narrow-focus, DRM-driven” modeling efforts and SNP results were consistent with the results published for these analogous studies. SNPs plan is to use the model to refine KPPs as advancements are realized but the power/value of the capability was demonstrated early on using credible SME inputs to both down-select specific technology options and to identify the need for the inclusion of in-space assembly as an architectural option.

While the model can rapidly and quantitatively evaluate technology impacts, a separate SE&I function is required to develop and evolve interface standards sufficient to assure effective CTE integration at the system level. This is especially true in an (anticipated) environment in which resources will dictate serial advancement of the CTEs in many instances.

One of the major keys to overall integration is the specification, design, and implementation of each of the CTE-to-CTE interfaces. It is likely that the hardware for each CTE will be developed on a stand-alone basis at least in early stages of the advancement effort. For example, the power conversion hardware in CTE-2 will not be tested with an actual reactor (CTE-1) as a heat source nor will it be connected to the actual PMAD hardware being developed in for CTE-3. Rather, the testing will be carried out using emulators at the interfaces. To ensure that the CTEs “fit” together, these emulators must be truly representative of the anticipated hardware and, for this, Interface Description Documents (IDD) for test development and implementation will be developed for each critical interface. While the IDDs will not rise to the level of rigor/control contained in typical Interface Control Documents required by flight programs, they will contain all necessary information to capture the major physical phenomena and engineering design requirements associated with each CTE-to-CTE interface. As examples, the IDD for the CTE-3/CTE-4 interface would contain the expected voltage-current start-up transient characteristics required to perform valid testing of the power management and distribution system in the absence of an actual thruster and the heat source used to emulate the reactor output at the CTE-1/CTE-2 interface would need to mimic both steady state heat transfer at the correct temperature and any thermal transients associated with start-up and shutdown. Preliminary IDDs will be developed by SNP SMEs after the CTE workshops. To ensure that CTE-specific modifications are made only with concurrence by developers on each side of the interface, the IDD’s will be held by SNPs SE&I lead who will also develop SNP’s policy for document reviews and revisions. Finally, SNP also will establish a forum for internal and external project information exchange of ongoing advancement activities to ensure open communication between ongoing technology development efforts.

Margin strategy: While flight projects employ very specific/quantified margins applied to specific spacecraft designs to be operated in a known architecture, the concept of margin is problematic when applied to NEP technology advancement due to the inherent uncertainty of working with subsystems in the TRL 3/AD^2 4+ class. That said, development efforts must still be focused on technologies that can be used in a credible mission architecture. Removing, for example, overly restrictive constraints such as “the spacecraft must fit under a single launch vehicle shroud,” provides the flexibility to add margin (increase total architecture mass or volume) by increasing the total number and/or types of launches. Based on findings to date, this may be required in any case – for example, if it is determined that the primary heat rejection system must be planar and flown edge-on to the sun, a separate launch followed by in-space assembly - not included in current “DRM-focused” missions - will be required (see Chapter 7). The TMP is entirely agnostic to LV selection and in-space assembly. As noted above, the technology estimations used to develop the starting KPPs are consistent with those used in contemporary point designs. System level threshold and target KPPs are currently defined based on technology advancement expectations with no fundamental technology breakthroughs required. Conservative ranges are used where appropriate to generate probabilistic estimates showing KPP credibility (e.g., both Hall and MPD thruster performance curves are taken from published performance data and run with ±5% absolute uncertainties - well beyond expected deviations). Based on these considerations, SNP does not carry a specific margins policy in the TMP. The KPPs cited are SME-vetted and shown to be sufficient to make NEP a credible propulsion alternative for crewed Mars missions studied to date. As the technologies advance, modeling of credible architectures will continue with results presented to SNP leadership for review and action if major changes to architecture requirements (e.g., multiple LV additions, target launch year eliminations, etc.) are identified.

It is noted that formal margin can be easily and quickly calculated using SMP-developed modeling tools once a mission is selected and programmatic constraints are imposed. At that point, variables like power level (i.e., number of required $\mathrm{MW_e}$-class modules) can be traded against total Δv/propellant mass required to optimize mission closure. Once the NEP power level, thruster type, and number/types of LV are chosen, mass and volume margins for the NEP system to the imposed constraints can be calculated. For preserving margin, this allows a trade-off of NEP system mass and volume (driven by power level) against propellant mass (flexibility in LV choice). As technology capabilities are demonstrated through the proposed advancement efforts, modeling efforts will shift more to the mode of specific architecture assessments with formal margin requirements.

On materials: Due to the long schedule, high cost, and inherent uncertainty in the development of new materials, no new material developments are planned for any of the TMP-proposed advancement efforts. Rather, existing materials (e.g., existing alloys) will be leveraged for all hardware designs. SME research indicates that the threshold KPP levels cited can be met with materials already commonly considered for NEP applications. Some target values may require more exotic materials not typically considered for NEP, but these have been identified as available. The NEP application is unique, and it is acknowledged that there may be technical gaps in material property databases over the span of NEP operating conditions or gaps in fabrication and assembly processes required to satisfy NEP design requirements. For these gaps, the corresponding fabrication process development and material characterization activities were considered and included in each subsystem's maturation plans as necessary.

1.6 Human Rating of a Spacecraft Propelled by an NEP System

While there is significant development that must occur before a human-rated system is required, this TMP has been developed with some consideration of this process. Human-rated systems typically have the most difficult hurdles to clear prior to usage on a flight mission, and the SNP project believes that certain design choices may make this future task easier to accomplish.

A workshop on human-rating of spacecraft using space nuclear propulsion systems was held in June 2021 (ref. [44]). The workshop provided illustrations of how other propulsion systems in the past have addressed human-rating requirements for system design and test, including present work on the electric propulsion system for the Power and Propulsion Element (PPE) of NASA's Lunar Gateway project. A major conclusion of the workshop was that developing the requirements on human-rating of the system will involve multiple entities, including NASA Safety and Mission Assurance (S&MA), the Human Spaceflight

Office, and NESC, among others. It was also explicitly noted that a mission taking humans to Mars and returning them safely would represent the largest single engineering endeavor ever undertaken at least in the realm of spaceflight, and perhaps in any engineering sphere, and crew safety and system reliability will drive requirements for such a mission.

Requirements for the human rating of space systems are described in NPR 8705.2 (ref. [45]). Until the human-rated system design and testing standards are fixed, SNP will assume a conservative approach with respect to these issues. Where human-rating aspects are addressed in the various sections of this TMP, the specific assumptions and means by which they are addressed are provided. As a starting point, presented in Figure 1.4 are multiple relevant design and construction (D&C) standards that will provide guidance and represent a starting point in developing the requirements for human rating a spacecraft using an NEP system. The project should endeavor to develop a set of human-rating requirements for an eventual flight system by the end of year two. This set of requirements should be subject to a NAR and serve as a baseline to guide future developmental planning.

Typical D&C Standards (not all)*

- **JSC 20793 Crewed Space Vehicle Battery Safety Requirements**
- **JSC 62809 Human Rated Spacecraft Pyrotechnic Specification**
- **JSC 65828 Structural Design Requirements and Factors of Safety for Spaceflight Hardware**
- **JSC 65829 Loads and Structural Dynamics Requirements for Spaceflight Hardware Applicable Sections for Deep Space Loads only**
- **JSC 67035 Best Practices and Guidelines (BP&G) for Thin Wall Pressure Boundaries (TWPB) for Human Spaceflight Applications**
- **MIL-STD-981 Design, Manufacturing and Quality Standards for Custom Electromagnetic Devices for Space Applications**
- **NASA-STD-4003 Electrical Bonding For NASA Launch Vehicles, Spacecraft, Payloads, And Flight Equipment Fully Applicable**
- **NASA-STD-5012 Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engine Fully Applicable**
- **NASA-STD-5017 Design and Development Requirements for Mechanisms**
- **NASA-STD-5018 Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Spaceflight Applications**
- **NASA-STD-5019 Fracture Control Requirements For Spaceflight Hardware**
- **NASA-STD-5020 Requirements for Threaded Fastening Systems in Spaceflight Hardware**
- **NASA-STD-6016 Standard Materials and Processes Requirements for Spacecraft**
- **NASA-STD-7009 Standard for Models and Simulations**
- **SMC-S-016 Test Requirements for Launch, Upper-Stage, and Space Vehicles**
- **SMC-S-010 Technical Requirements for Electronic Parts, Materials, and Processes Used In Space Vehicles**

Figure 1.4: Non-Exhaustive List of Applicable NASA Design and Construction (D&C) Documents and Specifications for Human Rating a System (ref. [44]).

Chapter 2

System and Mission Modeling and Simulation

Modeling and simulation (M&S) efforts play a major role in the development and maturation of each CTE. Those efforts are focused on developing predictive modeling capabilities validated by experimental test results that demonstrate an understanding of the physical processes and controllable parameters in each subsystem. They also provide the capability to project system lifetime, as the operational times for an NEP-powered system are so long (20,000 hours or greater for a human Mars mission).

At a level above each CTE are overall system and mission modeling. These are crucial to inform KPP threshold and target values for each CTE and to ensure that the CTE design choices under consideration result in a viable NEP system that meets system-level KPPs and achieves reference mission closure. As there are multiple technology options for each CTE under consideration within this TMP, each with various technology development challenges, system and mission models provide the capability to compare the expected system performance and vehicle mass associated with each technology option and support down-selection.

Overall NEP power system optimization is a function of many parameters. The CTEs of an NEP system are tightly coupled, requiring a model that accounts for the interdependencies between subsystems to accurately capture the system performance and vehicle mass for a given mission. Furthermore, as technology development progresses, demonstrated performance data and CTE modeling results must be incorporated into system models to refine the predictions on overall system performance and contributions to overall vehicle mass. A model that accurately does this can be used to optimize the overall system-level design and can ensure mission closure with appropriate margins that account for uncertainty in the analysis. It can also be used to generate useful comparisons between various technology options for each CTE, helping drive design choices of an overall system.

The system-level KPPs are included in Table 2.1. These were generated by overall NEP system and mission modeling already undertaken by the project and serve as the initial guides for the target and threshold performance required for the overall system and for each subsystem (Table 2.2 through Table 2.7). The "threshold" values shown in

Table 2.1 represents those values sufficient to make NEP a credible propulsion alternative for crewed Mars missions given the resulting vehicle architecture mass. The "target" values in the table are associated with higher performance technologies that enable a lower-mass vehicle architecture. Together, meeting the “threshold” subsystem-level KPPs results in meeting the “threshold” system-level KPPs. The “target” system-level α_{ps} requires some combination of exceeding the “threshold” subsystem-level KPPs, but not every “target” subsystem-level KPP must be met to achieve the target system-level α_{ps}. (ref. [46])

Table 2.1: System and Mission Model-generated Initial SNP Project NEP KPPs for Overall System and for each Subsystem.

KPP	**KPP Value**
Power system α_{ps} (kg/kW$_e$) (consists of CTEs 1, 2, 3, and 5)	24 kg/kW$_e$ (threshold), 13 kg/kW$_e$ (target)
Total electric propulsion power (CTE-4 power input)	2-4 MW$_e$
Electric propulsion efficiency and I_{sp}	Efficiency and I_{sp} relationship in Fig. 2.1 (operate at I_{sp} optimizing mission perf.)
Total electric propulsion thrust (function of efficiency, I_{sp} and power level)	65-120 N
Nominal mission duration	25,000 hours
CTE-1 outlet/CTE-2 inlet temp	1200 K (threshold), 1400 K (target)
CTE-4 total thruster operating time	27,000–32,000 hour (threshold), 30,000–32,000 hour (target) (dependent on propulsion system option)

Table 2.2: Reactor and Coolant Subsystem (RXS) (CTE-1) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Power Conversion Inlet Temperature (PCIT)	1200 K	1400 K	Operation at 1400 significantly reduces radiator α while simultaneously increasing PCS efficiency. This value corresponds to PCS turbine inlet temperature.
CTE-1 α (kg/kW$_e$)	6	4.5	Threshold and target α parameters are derived from SME input and informed by system & mission analysis

KPP	**Range**	**Significance**
CTE-1 Power (MW-thermal, MW$_{th}$)	5–16 (total) 5–8 (per unit)	8 MW$_{th}$ reactor delivering working fluid to the turbine at 1200 K coupled with a PCS at threshold thermal efficiency (e.g., 25% at 1200/450 K) corresponds to an electrical output of 2 MW$_e$. A 5 MW$_{th}$ reactor at 1400 K and target thermal efficiency (e.g., 40% at 1400/323 K) of PCS provides 2 MW$_e$. Two reactors or a scaled-up design would be needed to provide up to 4 MW$_e$. See Table **??** for CTE-2 thermal efficiency definition.
Lifetime (MW$_{th}$-years)	20-32	Effective full power years affects both fissile material loading and material performance requirements of a single reactor. Corresponds to reactor thermal power over a nominal operational lifetime of 3 years with margin.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad	Neutron and gamma dose limits for electronic equipment.

Table 2.3: Power Conversion Subsystem (PCS) (CTE-2) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Power Conversion Inlet Temperature (PCIT)	1200 K	1400 K	Operation at 1400 significantly reduces radiator α while simultaneously increasing PCS efficiency.
Thermal efficiency	40% of Carnot efficiency (e.g., 25% at 1200/450 K)	52% of Carnot efficiency (e.g., 40% at 1400/323 K)	Increased thermal efficiency reduces the amount of waste heat that must be rejected from the NEP system and reduces the thermal power requirements of the reactor (CTE-1). Thermal efficiency is dependent upon the thermodynamic efficiency of the PCS design and CTE-2 interfaces with other subsystems.
CTE-2 α kg/kW$_e$)	3	2	Threshold and target α parameters are derived from mission analysis. Current models estimate that CTE-2 contribution to the overall alpha is ∼10%. These values are preliminary and subject to revision as the overall achievable system α is better quantified.
KPP	**Range**		**Significance**
Total Subsystem Power/Per Unit Power (MW$_e$)	2-4 / 0.5-1		Ranges are indicative of evolving mission needs. System will likely use multiple PCS units each ranging from 0.5 – 1.0 MW$_e$.
Compressor Inlet Temperature (CIT)	320-450 K		Efficiency and radiator materials selection influenced temperature range. *CIT is provided for the thermal efficiency KPP as reference only.
Lifetime (hours)	25,000	32,000	Human Mars mission is estimated to be 20,000–30,000 hrs of operation.

Table 2.4: Power Management and Distribution Subsystem (PMAD) (CTE-3) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Power per Generator (MW_e)	0.5	1.0	1 MW_e “building blocks” are key to overall technology maturation strategy – decision on number of units per MW_e is a research and development Milestone
Generator Output	∼1 kV / 2 kHz		SME-generated preliminary AC voltage characteristics subject to early project trade studies
CTE-3 α (kg/kW_e)	4	3	Threshold and target α values derived from mission analysis and SME technical inputs
Subsystem Efficiency (η in %)	93	95	Threshold and target η values derived from mission analysis and SME technical inputs
Lifetime (Years)	3	10	3 years provides margin for single (2.5 year) human mission to Mars, 10 years enables multi-trip reuse
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for electronic equipment.

Table 2.5: Hall Thruster Electric Propulsion Subsystem (EPS) (CTE-4) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Power per Thruster (MW_e)	0.1-0.3		1 MW_e “building blocks” are key to overall technology maturation strategy – number of units to reach MW_e are to be determined through an initial SME workshop.
CTE-4 Hall α (per string in kg/kW_e)	5	3	CTE-4 Hall α (per string in kg/kW_e)
Thruster Performance	η and I_{sp} shown in Figure 2.1		Performance values based on experimental data obtained from SNP SMEs. Performance projection from SOA sufficient for mission closure – no research and development required for performance improvement. (Curve represents nominal expected performance from available data. Mission modeling assumes ±5% absolute uncertainty to estimate mission closure mass impact.)
PPU/DDU Efficiency (η in %)	95	97	PPU/DDU Efficiency (η in %)
Total thruster operating time (hours)	25,000	30,000	Operating time assumes an approximate 10,000 hr spiral time from low-Earth orbit (LEO) to near-rectilinear halo orbit (NRHO). Thruster lifetime requirements would be significantly reduced with direct injection to (or assembly in) NRHO.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for power electronics.

Table 2.6: MPD Thruster Electric Propulsion Subsystem (EPS) (CTE-4) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Power per Thruster (MW_e)	0.5	1.0	1 MW_e “building blocks” are key to overall technology maturation strategy – decision on power per thruster midway through TRL 4 testing.
CTE-4 MPD α (per string in kg/kW_e)	5	3	Threshold and target values derived from mission analysis and SME technical inputs
Thruster Performance	η and I_{sp} shown in Figure 2.1		Performance values based on experimental data obtained from SNP SMEs. Performance projection from SOA sufficient for mission closure – no research and development required for performance improvement. (Curve represents nominal expected performance from available data. Mission modeling assumes ±5% absolute uncertainty to estimate mission closure mass impact.)
PPU Efficiency (η in %)	93	95	Threshold and target η values derived from mission analysis and SME technical inputs
Total thruster operating time (hours)	27,000	32,000	Threshold provides margin for single (2.5 year) human mission to Mars, including allocation for spiral up from aggregation orbit; target enables multi-trip reuse. Includes spiral up. Operating time assumes an approximate 10,000 hr spiral time from low-Earth orbit (LEO) to near-rectilinear halo orbit (NRHO). Thruster lifetime requirements would be significantly reduced with direct injection to (or assembly in) NRHO.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for power electronics.

Table 2.7: Primary Heat Rejection Subsystem (PHRS) (CTE-5) KPPs.

KPP	**Threshold**	**Target**	**Significance**
Mass per Area of Panels & Transport ($\mathrm{kg/m^2}$)	4.5	3.0	Primary heat rejection assembly mass without system-specific structure.
Mass per Area of Primary Boom Structure ($\mathrm{kg/m^2}$)	2	1	Structural mass (scales with heat rejection assembly mass and CTE-1 mass).
Total Power Radiated ($\mathrm{MW_{th}}/\mathrm{MW_e}$)	1.5-3		Assumes power conversion efficiency range (25-40%) consistent with CTE-2 KPP range with 1.5-3 $\mathrm{MW_{th}}$ to dissipate (3 – 12 $\mathrm{MW_{th}}$ total) per $\mathrm{MW_e}$ generated.
End-of-Life Emissivity	0.85	0.9	End-of-Life emissivity of radiator panels.
CTE-5 Outlet Temperature (K)	320-450		Cold-side trunkline return; Encompasses the range of outlet temperature expected to minimize system α balanced with limiting radiator area given the PCIT KPP; corresponds to CIT KPP.
CTE-5 Inlet Temperature (K)	550-750		Hot-side trunkline inlet; Encompasses the range of CTE interface temperatures expected to minimize system α or radiator area given the PCIT KPP range.
Lifetime (Years)	3	10	3 years provides margin for single (2.5 year) human mission to Mars, 10 years enables multi-trip reuse

The KPPs that have a major effect on the overall system-level result are associated with the power generation system specific mass (α_{ps}) and the performance of the propulsion system. Additional factors that will have a large effect on the overall design choices are desired system lifetime and requirements on fault tolerance or redundancy in each subsystem. In an electric thruster, there is a relationship between the power consumed by an electric thruster and the thrust and I_{sp} produced. These are typically given as a set of curves (one for each input electrical power level) relating thruster efficiency (defined as the jet power of propellant exiting the thruster over the electrical power input to the thruster) and the I_{sp}, as in Figure 2.1.

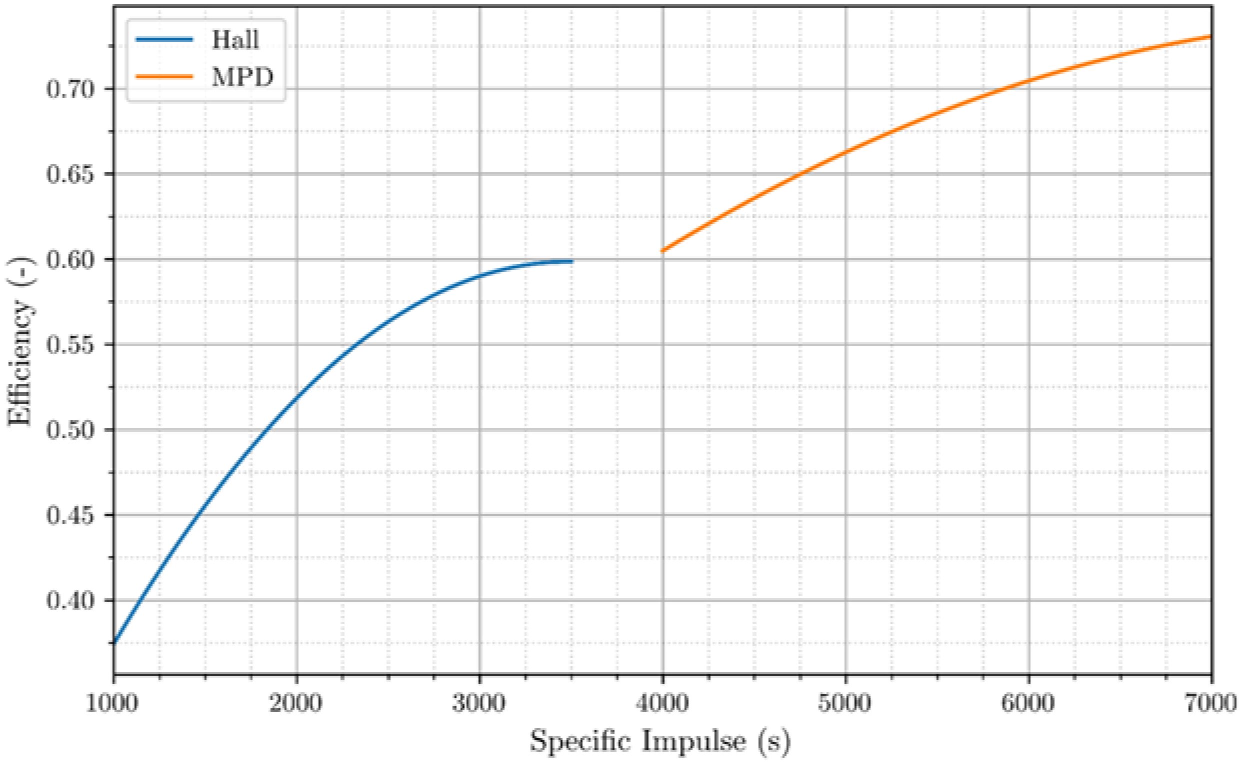


Figure 2.1: The relationship between thruster efficiency and specific impulse for Xe-fed Hall and Li-fed MPD thrusters.

Using those curves as the limits on performance for a thruster allows one to bound the overall power required by the electric thrusters for a mission of interest. If the scaling of masses for each subsystem is known as a function of input power (or some other derivable parameter), then the specific mass of the power system α_{ps} (defined as the mass per unit electrical power of an NEP power generation system comprising CTEs 1, 2, 3, and 5) can be calculated and optimized for various parameters of interest. Examples of optimizations may include minimum trip time, minimum vehicle initial mass, minimum system power required, etc.

An important KPP for each CTE is its mass per unit power (denoted by α) or mass per unit area in the case of the PHRS. While this document defines α KPPs for individual CTEs, the trade-offs in the masses of each CTE involve nonlinear relationships. These relationships are developed and implemented based upon system- and subsystem-level performance and mass modeling of various point designs and using parametric power system models supported by available data. During modeling and technology development some CTE α values may increase, and some may decrease as a function of various technology choices and implementations, but the important top-level controlling parameter and the one that is the ultimate basis for power system comparisons is the overall power system α_{ps}.

Over the past 50 years, various models have been developed to support NEP projects and mission concept studies and analyses. As part of the Prometheus Program, the JIMO project developed concepts for NEP to be used to deliver scientific payloads to Jupiter's moons. In JIMO, system level models were used to estimate the performance and mass of the NEP power system (ref. [47]) Design Reference Architecture 5.0 Addendum 2 assessed NEP as an option for a crewed mission to Mars (ref. [48]). This study included the conceptual design and modeling of multi-megawatt NEP-powered crewed vehicle concepts. The study included identification of key technologies and sensitivities and development of a detailed concept of operations. Mission analysis of an NEP-powered human mission executing a two-year opposition-class mission to Mars mission was performed for specific point designs and technology selections under MTAS (ref. [49]).

An integrated performance and mass model for NEP system evaluation has been the subject of recent investigations (refs. [21, 22]) and has been used to guide the development of NEP KPPs and explore a wide parameter space of mission options and technology choices. System level models include a mission model, a vehicle/spacecraft model, and a performance & mass model of the CTEs, here called the NEP system integration model or NEP-SIM. NEP-SIM contains models of each CTE and their respective interfaces, and its results are incorporated into the vehicle and mission model to ensure internal self-consistency and mission closure. NEP-SIM uses flexible modules for each of the CTEs shown in Figure 1.1. In the system model, each module can be tailored for the specific technologies under assessment (e.g., HPR (heat pipe-cooled reactor) or HTGR (high temperature gas-cooled reactor) for CTE-1, Hall- or MPD-based EPS for CTE-4). The best available technical data and technology-specific models provided by SMEs and found through independent review are used in the calculation of system-level parameters like α_{ps}. KPPs are developed based on the best available technology inputs and uncertainties in those data. Over the course of CTE development and maturation as outlined in this TMP, the results of hardware maturation and updated performance and mass scaling information will be incorporated into new systems-level trade studies. A simple diagram of the feedback loop employed by this TMP to perform current and future technology evaluation is shown in Figure 2.2. This iterative approach reduces the risk of the development program failing to meet system-level KPPs and allows resources to be allocated to the most important risks as they become evident.

As the SNP project progresses through the execution of this TMP, the modeling effort will be expanded and used to 1) refine the KPPs in the near-term to ensure mission closure with sufficient margin for the level of uncertainty in the data inputs, 2) down-select to specific technologies for each CTE as higher-quality inputs become available, and 3) provide increasing fidelity for more detailed analyses (e.g., reliability, transient behavior). Such a set of coupled models can also be used to evaluate the payoff of lower TRL technologies that may not be ready for immediate implementation but that may, through their enhancement of the system, merit some level of present investment. A block/flow diagram showing the existing

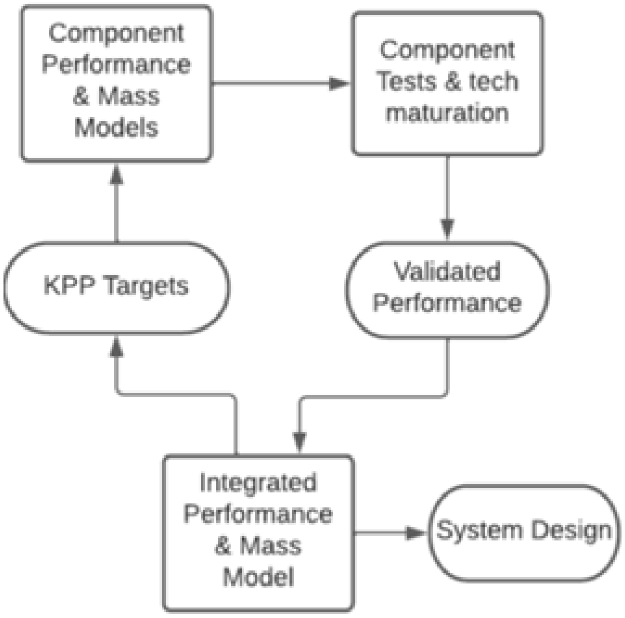


Figure 2.2: Simple feedback loop system model process flow used in this TMP to update KPPs as more data is generated.

and anticipated system and mission model capabilities and their relationship to component models that will be developed and refined for each CTE as they execute their respective TMP tasks is shown in Figure 2.3. As component, assembly, and CTE models are developed within CTE activities, they will be incorporated into the system model at a level of fidelity appropriate to address the system-level goals. Continuous upgrades to the system models are performed to incorporate these newly available higher-fidelity data on each CTE and to evaluate current and new technologies of interest. Periodic NARs will be held to evaluate the direction and progress of the system and mission modeling and simulation effort.

2.1 Mission & Campaign Model

The mission and campaign model includes the trajectory and optimization of the initial mass of the vehicle based on the Δv needed to close the mission. To minimize initial mass, the model can optimize the division of Δv between the NEP system and an additional high-thrust chemical propulsion system used for departure and arrival burns. There are multiple ground rules that affect the model and the results that inform the KPP targets in this TMP. These include the type of mission (Mars opposition or conjunction-class, transit using or not using a Venus flyby, mission abort scenarios), the mission opportunity (e.g., 2039, 2041), the aggregation orbit for a multiple-launch vehicle, constraints on the Earth departure orbit (e.g., requirement to rendezvous in NRHO with a habitat module), the masses of payload to be delivered to Mars and return to Earth, any constraint on maximum transit or total mission duration, and any constraint on the duration of operations in the Mars sphere of influence (SOI), to name a few. Analyses performed in support of this TMP are based on the set of ground rules provided in Table 2.8, corresponding to a human mission to Mars of interest to

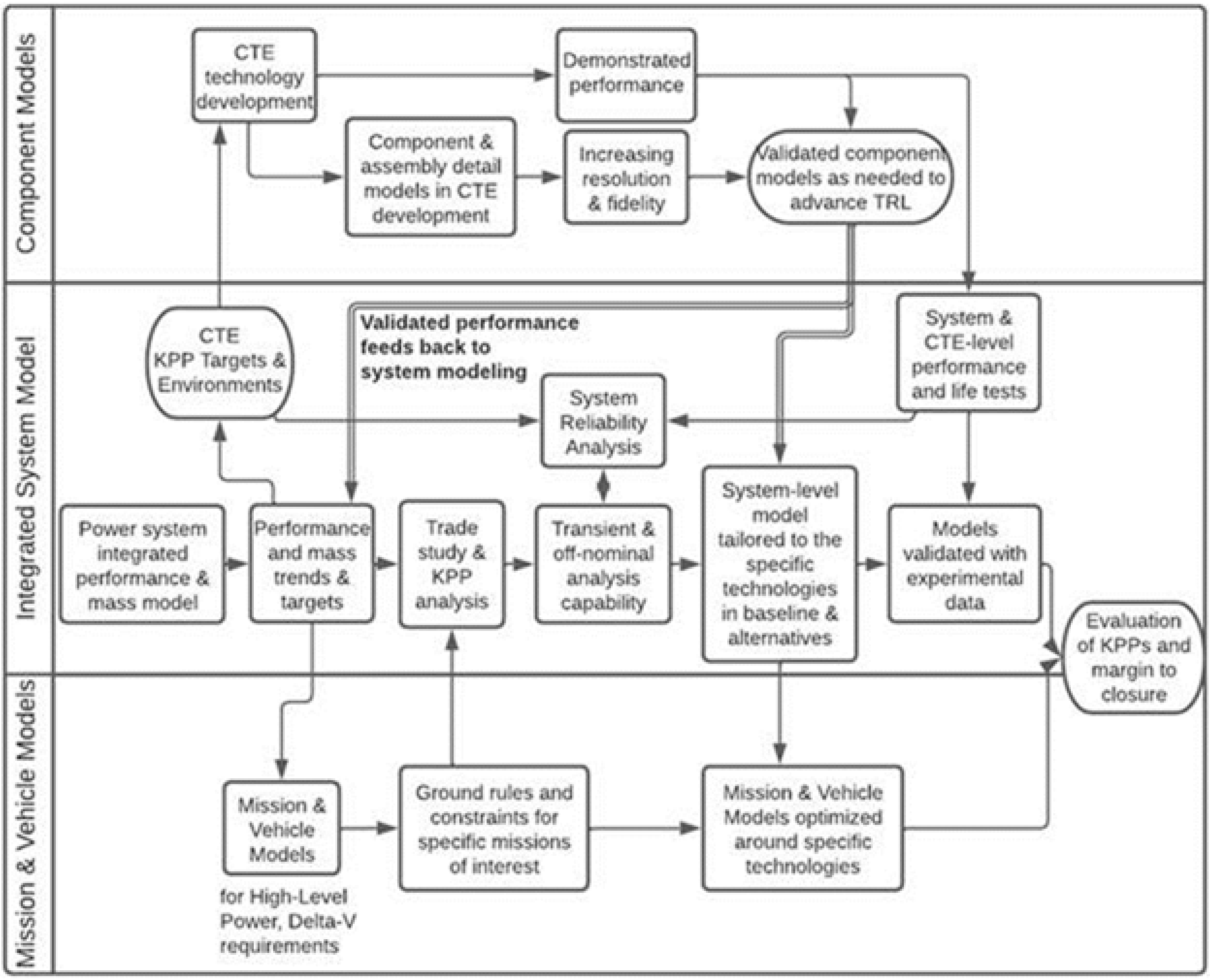


Figure 2.3: Detailed block/flow of modular NEP system model with all current and envisioned future capabilities.

NASA and subject of recent investigations (performed with ground rules and assumptions not relevant to TMP development). The model identifies how different NEP technology choices satisfy mission needs and can investigate the effect of variations in these ground rules. The model could in the future be used to address questions such as reusability of an NEP system for a multi-mission campaign and sizing of cargo or flight qualification mission. The model will also be used to support assessment of various thruster reliability/redundancy configurations.

As technology development progresses, this model will need to provide analysis of margin to closure for the mission based on demonstrated achievement of KPPs for each CTE. These analyses will be performed against specific missions of interest with appropriate architecture constraints.

Table 2.8: Mission and campaign model ground rules and assumptions.

Ground Rule or Assumption	**Parameter Value**
Mission Class	Opposition
Mission Opportunity (year)	2039, 2042
Mars SOI Stay Duration	50 days
Total Trip Duration	730 days
Starting and Ending Orbital Location	NRHO
Mars Parking Orbit	5 Sol
Chemical Prop I_{sp}	360 sec
Reaction Control System I_{sp}	315 sec
Chemical Prop Thrust	50 klb_f
Payload/Habitat Mass	45 metric ton

2.2 Vehicle Architecture & Spacecraft Model

The vehicle architecture and spacecraft model represent the dry mass model of the spacecraft that is used in the mission modeling described earlier. This modeling includes the assembly of the NEP vehicle around the five CTEs and the chemical propulsion stage. The model accounts for major variations in the vehicle design that result from technology choices. The major variants identified through modeling to date include the use of different electric propulsion systems (e.g., Xe-fed Hall thrusters vs. Li-fed MPD thrusters) and differences associated with the NEP system power level. Other propellants could be considered but have not to date due to their lower performance or lower maturity. Ultimately, there will likely need to be a vehicle model for each thruster type being developed. Present modeling uses a constant dry mass to represent systems that don't scale with input power and a specific mass (mass per unit power) to account for the systems that scale with power. There are also vehicle masses that scale with the overall propellant requirement, which are in turn influenced by the I_{sp} of the electric and chemical propulsion systems and the Δv split between the low and high thrust systems. As work on this TMP progresses, this model will be matured to address assumptions in the modeling and constraints of interest. These major assumptions and constraints include the number and type of launch vehicles, the frequency of launches, any in-space assembly concepts and capabilities that may become available, and the potential to perform in-space refueling of propellant tanks.

2.3 NEP System Design and Integration Model

The NEP System Design and Integration model includes a mass model for each CTE and an overall performance analysis of the power conversion cycle, starting from power production in the reactor and modeling the flow and conversion of power to either the electrical load (CTE-4 EPS) or the thermal load (CTE-5 PHRS). The design and integration model also accounts for the interfaces among the CTEs as illustrated in Figure 2.4.

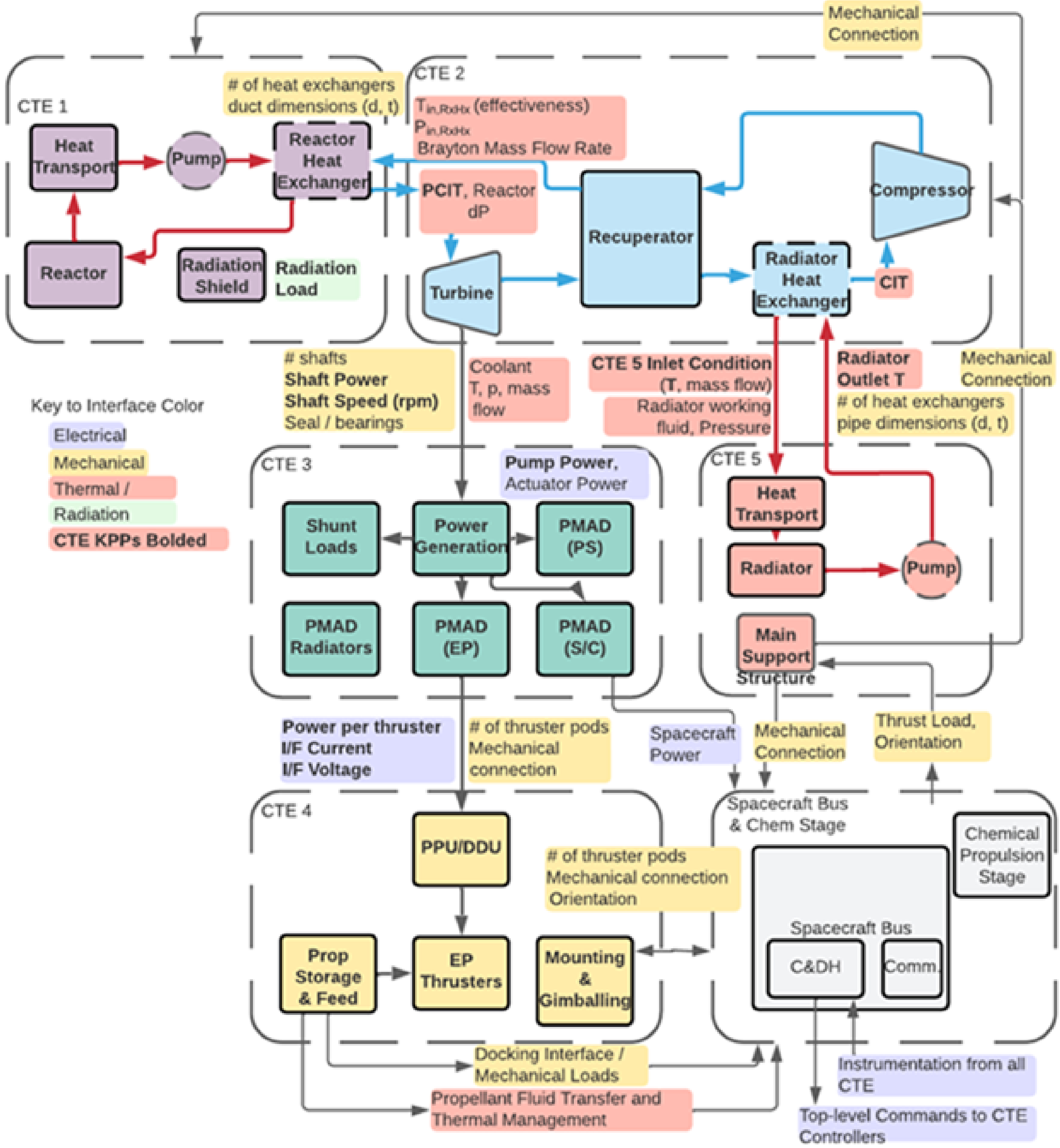


Figure 2.4: CTE-level block diagram with interfaces between each CTE highlighted.

The model allows for the effect of KPP choices, such as the turbine or compressor inlet temperatures, or design parameters, such as the turbine pressure ratio, to be understood and optimized at the system level. This permits the quantification and subsequent comparison between the system mass and performance associated with different technology options (i.e., HTGR, HPR, etc.). The CTEs in the model are modular, which allows for upgrading of the elements as additional data become available, or for swapping out elements to make the comparisons between different option. At the system-level, some of the major technology options and design decisions that affect the CTE KPP targets include the choice of Brayton cycle working fluid, the configuration of the power conversion cycle (number of separate working fluids, compression/expansion stages, or heat exchange stages), the layout of the PHRS (geometry and configuration of series and parallel pipes/ducts in the radiators), and reliability/redundancy approach. Modeling of this type has so far been used to inform KPP selection and any initial technology down-selections that guided the design and maturation choices outlined in this TMP.

The NEP system design & integration model will need to include the capability to perform transient analyses of the system for situations including startup and shutdown as well as off-nominal operation and failures including loss of either a power conversion unit or a thruster. A complete system reliability and life model will be needed to evaluate system-level redundancy trades. These capabilities will support a system-level failure modes and effects analysis (FMEA), which will accompany the FMEA performed for maturation of technologies in each separate CTE. For each CTE, there are multiple viable approaches to redundancy that may manifest at either the CTE level (e.g., radiator heat transport loop redundancy) or at the system level (e.g., use of complete back-up power conversion units, cross-strapping of electrical systems, setting concept of operations (CONOPS) to nominally operate systems at either full-power or de-rated).

As technology development progresses, this model will also be used to determine quantities such as performance margins, radiator area, and α_{ps} based on demonstrated and extrapolated performance of various subsystems and the expected operating environments. Uncertainty in the performance data for each CTE will decrease as development progresses, and the modeling must account for the present and future level of uncertainty in the inputs when stating confidence in the calculated outputs and margins.

2.4 Comprehensive Environment Models

To support technology development, a complete set of environment models is needed. These represent the environments seen by the NEP system throughout the full mission and inform requirements on each CTE. Table 2.9 identifies five environment models that will eventually be required for the development of a full mission and integrated vehicle design. A subset of these will be useful in defining relevant test environments for TRL 5 demonstration tests.

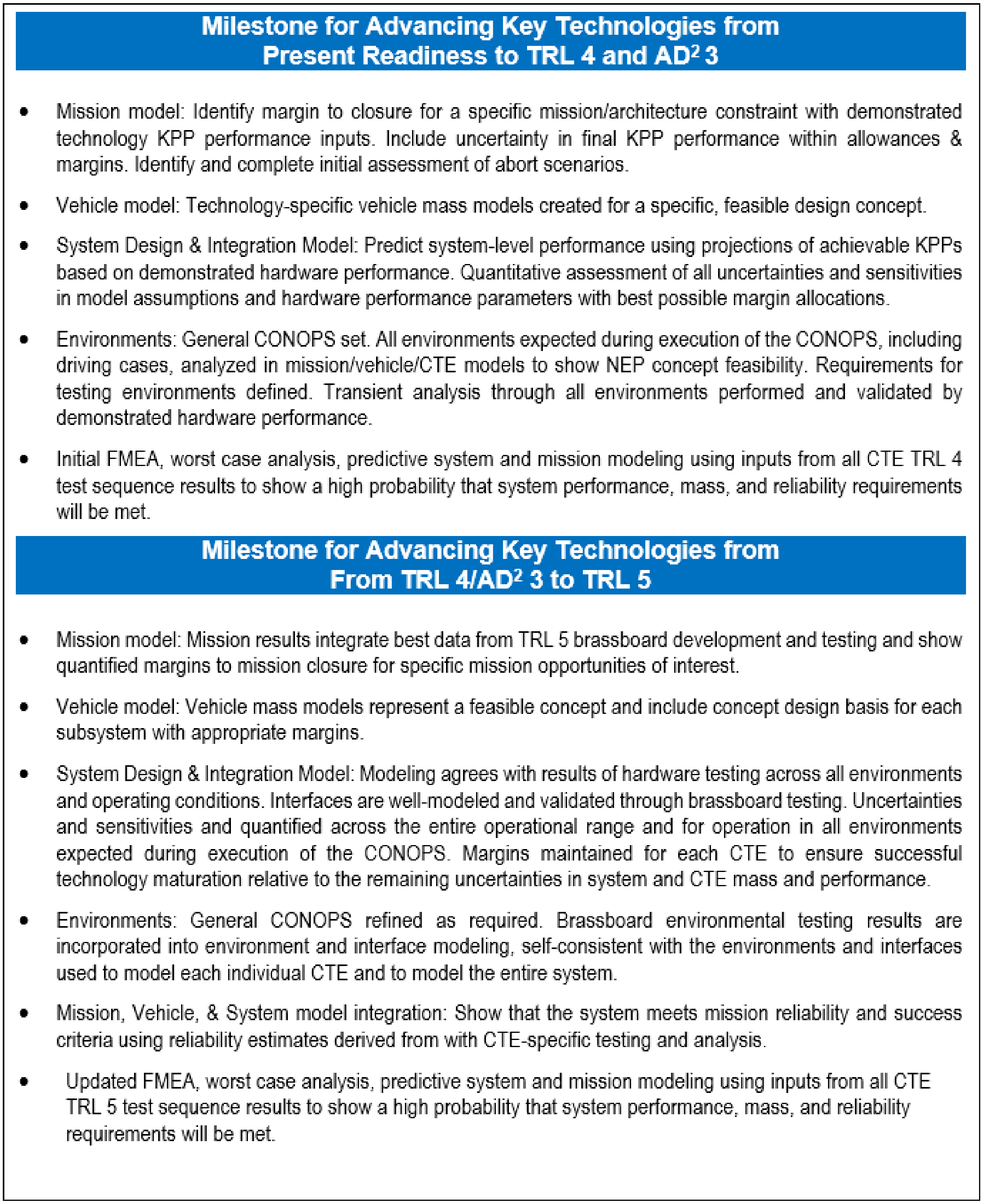
Table 2.9: Environment Models and Capability Needs.

Environment Model	**Capability Needs Description**
Thermal environments for all orbits and transits	Solar, space view, albedo environments for each mission segment. The environments seen by each CTE are a function of vehicle configuration (e.g., relative direction of thrusters and radiators) and CONOPS requirements (e.g., thrust vector pointing of EP and chemical burn maneuvers). The thermal environment experience by each CTE must be provided based on these system-level considerations.
Radiation	The space radiation environment must be defined for electronics, reactor and other sensitive components within the CTE as a function of mission and trajectory parameters. The radiation load produced by the reactor is a KPP of that system and an interface between it and the other five CTEs.
MMOD	The MMOD environment may be a design-driving environment for some of the CTEs (e.g., to provide reliability and prevention of working fluid loss to systems such as the PCS). This environment must be defined as a function of the mission and vehicle ground rules.
Ground Handling Loads	Ground handling loads associated with transport and assembly, including both static and dynamic loads.
Launch Loads	Launch loads (including static, dynamic, shock, acoustic, in-fairing thermal) must be defined to provide requirements for CTE design & development. The ground rules for vehicle modeling and the system configuration decisions affect the loads seen by each CTE.
In-space Loads	In-space loads resulting from the CONOPS of low- and high-thrust propulsive maneuvers determine the structural environment for design in the deployed state for each CTE and may be driving requirements for the PHRS structure.

2.5 TRL Advancement Criteria

The system and mission modeling and simulation activities described in this section will be ongoing and concurrent tasks throughout the execution of this TMP. This is unlike the hardware and testing-heavy schedule for CTEs 1-5, where there are specific predecessor and successor tasks for development. Consequently, we do not here produce a schedule, since it would only show all things occurring at once. However, we do describe specific tasks needed to advance system and mission modeling and simulation capabilities to TRL 4 and TRL 5.

It is expected that advancement of these capabilities will occur on a schedule mirroring CTE technology advancement since the former is supported by development and advancement of the latter. The developmental milestones are described in Figure 2.5. Model and simulation development follows NASA-STD-7009A. (ref. [50])



Milestone for Advancing Key Technologies from Present Readiness to TRL 4 and AD^2 3

- Mission model: Identify margin to closure for a specific mission/architecture constraint with demonstrated technology KPP performance inputs. Include uncertainty in final KPP performance within allowances & margins. Identify and complete initial assessment of abort scenarios.
- Vehicle model: Technology-specific vehicle mass models created for a specific, feasible design concept.
- System Design & Integration Model: Predict system-level performance using projections of achievable KPPs based on demonstrated hardware performance. Quantitative assessment of all uncertainties and sensitivities in model assumptions and hardware performance parameters with best possible margin allocations.
- Environments: General CONOPS set. All environments expected during execution of the CONOPS, including driving cases, analyzed in mission/vehicle/CTE models to show NEP concept feasibility. Requirements for testing environments defined. Transient analysis through all environments performed and validated by demonstrated hardware performance.
- Initial FMEA, worst case analysis, predictive system and mission modeling using inputs from all CTE TRL 4 test sequence results to show a high probability that system performance, mass, and reliability requirements will be met.

Milestone for Advancing Key Technologies from From TRL 4/AD^2 3 to TRL 5

- Mission model: Mission results integrate best data from TRL 5 brassboard development and testing and show quantified margins to mission closure for specific mission opportunities of interest.
- Vehicle model: Vehicle mass models represent a feasible concept and include concept design basis for each subsystem with appropriate margins.
- System Design & Integration Model: Modeling agrees with results of hardware testing across all environments and operating conditions. Interfaces are well-modeled and validated through brassboard testing. Uncertainties and sensitivities and quantified across the entire operational range and for operation in all environments expected during execution of the CONOPS. Margins maintained for each CTE to ensure successful technology maturation relative to the remaining uncertainties in system and CTE mass and performance.
- Environments: General CONOPS refined as required. Brassboard environmental testing results are incorporated into environment and interface modeling, self-consistent with the environments and interfaces used to model each individual CTE and to model the entire system.
- Mission, Vehicle, & System model integration: Show that the system meets mission reliability and success criteria using reliability estimates derived from with CTE-specific testing and analysis.
- Updated FMEA, worst case analysis, predictive system and mission modeling using inputs from all CTE TRL 5 test sequence results to show a high probability that system performance, mass, and reliability requirements will be met.

Figure 2.5: Key Milestones in the Modeling and Simulation Advancement Strategy.

Chapter 3

Advancement Plan – CTE-1: Reactor and Coolant Subsystem (RXS)

The reactor in a high-power (MW$_e$-class) NEP system relies on a careful balance between thermal power generation via nuclear fission and the cooling of the reactor to manage and control the thermal energy balance and excess heat generated in the reactor and ensure stable long-term operation needed for deep space missions. To achieve this, the RXS (collectively referred to here as Critical Technology Element 1 or CTE-1) is composed of the fission reactor, including the associated structural, control, and core shielding components, and a cooling loop. The latter extracts heat from the reactor and conveys it to the interface between the reactor and the power conversion subsystem (CTE-2).

3.1 Introduction

Many conceptual NEP reactor designs have been designed over the past six decades. These include, for example, the SNAP-8 and SNAP-10A developed in the 1960s (refs. [8, 50, 51]) work on the SP-100 design, performed in conjunction with NASA's SEI in the 1990s (refs. [9, 10, 11, 12, 52]) and the design for Project Prometheus in the early 2000s (refs. [16, 17, 50, 53]).

Of these, the 0.5 kW$_e$-class SNAP-10A reactor was the only United States (US) reactor ever launched into space under the Space Nuclear Auxiliary Power Orbital Test (SNAPSHOT) program (ref. [2, 8, 54]). This mission also demonstrated the use of a nuclear reactor to power an electric propulsion (ion thruster) system. The SP-100 and Project Prometheus reactors were never fabricated, but their designs targeted 100 to 200 kW$_e$, respectively. While components and working fluids vary across different NEP reactor designs, all share major assemblies with similar functionality. Figure 3.1 shows a simplified block diagram of a notional space NEP reactor. The major assemblies that are key to reactor advancement to TRL 4 and 5 are identified in the figure. These will be developed on the component and assembly levels as required followed by demonstrations on the integrated (CTE) level to achieve TRL 4 and then TRL 5. More recently, advanced reactor programs for both government and commercial applications have been initiated and it is possible that results from these programs may be leveraged for NEP RXS development (refs. [55, 56, 57, 58]). Later in this chapter we summarize the ongoing reactor development efforts that could be leveraged for accelerating NEP technology development.

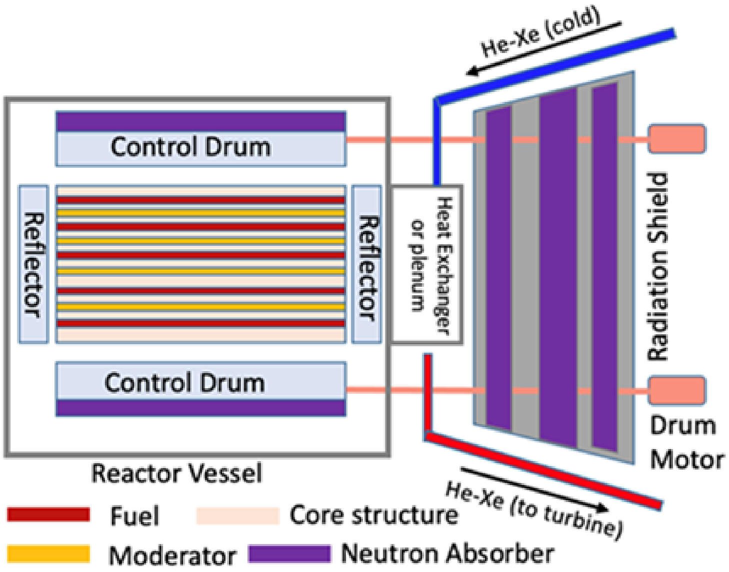


Figure 3.1: Simplified Block Diagram of a Space Nuclear Reactor for NEP

In keeping with the robust SE&I philosophy described in the Introduction, a detailed Interface Description Document (IDD) will be developed for the external CTE-1/CTE-2 interfaces. Preliminary descriptions of this interface are discussed in this section but a stand-alone IDD will be developed by SNP SMEs and provided to the SNP CTE-1 lead after discussion at the opening workshop. This IDD will be reviewed by SNP, circulated for SME evaluation if required, and then finalized and kept by the SNP SE&I. The document will be reviewed and revised as needed at each major relevant milestone and then reviewed as part of the NARs planned for technology advancement verification with NAR approval of the IDD as a condition for advancement. In addition, IDD's will be generated for each MA-to-MA interface to ensure compatibility as efforts on the RXS and PCS systems progress. These IDDs will be kept by the CTE lead and reviewed with the SNP SE&I lead and/or SMEs as needed. It is also noted that all applicable standards, including those required for human rating, will be identified and applied if appropriate so that the hardware developed to achieve TRL 5 will translate to TRL 6/prototype/flight-like designs without requiring any appreciable research and maturation.

The WBS for the RXS development effort is shown in Figure 3.2. It is anticipated that extensive M&S efforts with specialized simulation codes and data sets will be required for component and major assembly maturation. The dedicated M&S tasks encompass the effort required to assure that 1) reactor components are functional on the CTE level, 2) credible endurance projections can be forecast, and 3) failure modes and effects are understood at the level required to move to the development and demonstration of an integrated TRL 6 reactor.

All past space nuclear reactor designs have been based on highly enriched uranium (HEU) fuels. According to current US policy, "the use of highly enriched uranium (HEU) in [Space

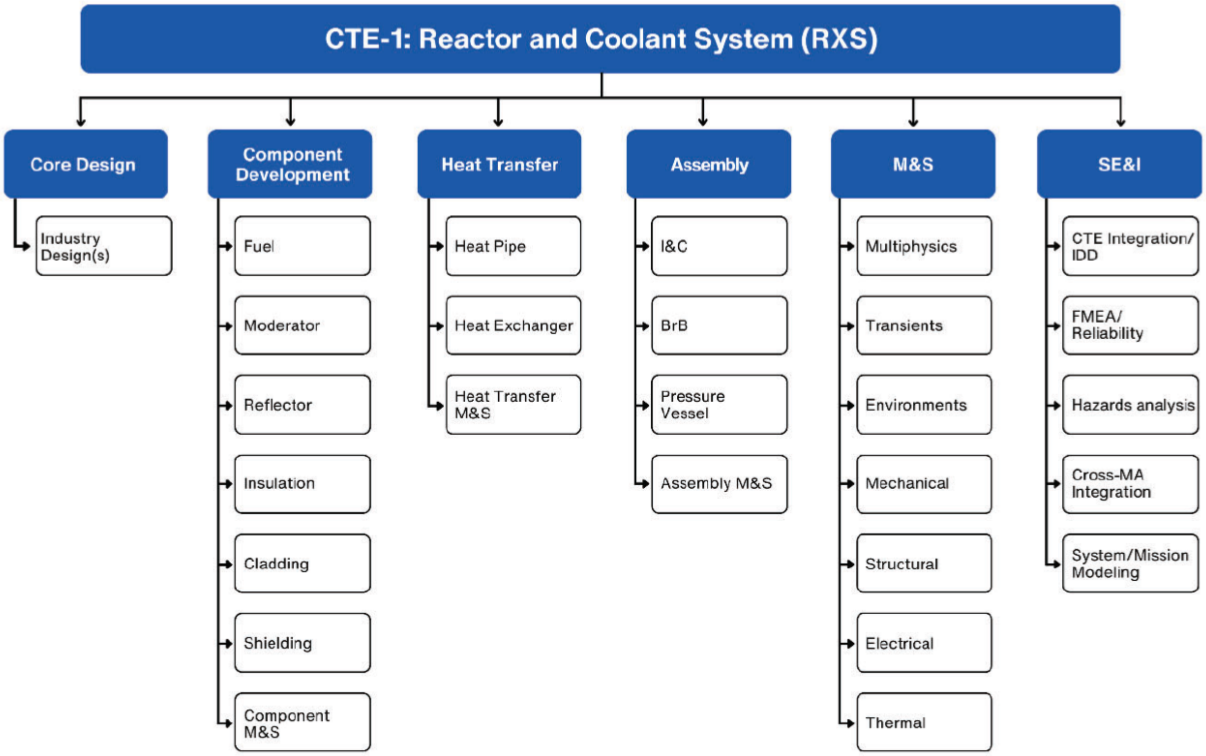


Figure 3.2: WBS for RXS Subsystem Development Management.

Nuclear Power and Propulsion] systems should be limited to applications for which the mission would not be viable with other nuclear fuels or non-nuclear power sources" (ref. [59]). SNP is adhering to this policy and basing its design strategy on high-assay low enriched uranium (HALEU) fuel. This choice also simplifies a major reactor design decision – selection of the neutron energy spectrum domain. Both fast and thermal spectrum reactors have been considered for NEP systems in the past. SNAP-10A used a thermal spectrum reactor while both the proposed SP-100 and Project Prometheus reactors were to employ fast spectrum designs. Thermal spectrum reactors with HALEU require less fissile material (^{235}U) than their fast spectrum counterparts. These and other factors, such as availability of testing and qualification infrastructure, formed the basis for developing this TMP.

Over the past six decades, there have been many crewed Mars, MW$_e$-class NEP architecture studies (refs. [17, 18, 19, 20, 21, 22, 23, 24, 25, 60, 61, 62, 63, 64, 65, 66, 48, 67, 68, 69]) with typical power levels ranging from 2 to 10 MW$_e$. Using inputs from these studies and other sources, the NEP system-level modeling methodology described in Chapter 2 was used to develop an initial set of KPPs to guide technology advancement efforts. This initial set of KPPs is shown in Table 3.1. Both threshold and target goals are shown. The former is viewed as the minimum values required to meet reactor α requirements with minimal margin given current uncertainties in technology projections. The target goals, if met, would provide a reactor specific mass significantly below the minimum requirements and provide margin on the system level.

Table 3.1: KPP Guidance for CTE-1 Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Power Conversion Inlet Temperature (PCIT, K)	1200	1400	Operation at 1400 significantly reduces radiator alpha while simultaneously increasing PCS efficiency. This value corresponds to PCS turbine inlet temperature.
CTE-1 α (kg/kW$_e$)	6	4.5	Threshold and target α parameters are derived from SME input and informed by system & mission analysis

KPP	**Range**	**Significance**
CTE-1 Power (MW-thermal, MW$_{th}$)	5–16 (total) 5–8 (per unit)	8 MW$_{th}$ reactor delivering working fluid to the turbine at 1200 K coupled with a PCS at threshold thermal efficiency (e.g., 25% at 1200/450 K) corresponds to an electrical output of 2 MW$_e$. A 5 MW$_{th}$ reactor at 1400 K outlet temperature and target thermal efficiency (e.g., 40% at 1400/323 K) of PCS provides 2 MW$_e$. Two reactors or a scaled-up design would be needed to provide up to 4 MW$_e$. See Table 4.1 for CTE-2 thermal efficiency KPP definition.
Lifetime (MW$_{th}$-years)	20-32	Effective full power years affects fissile material loading and material performance requirements of a single reactor. Corresponds to reactor thermal power over a nominal operational lifetime of 3 years with margin.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad	Neutron and gamma dose limits for electronic equipment.

To support technology maturation decision-making, SNP held a broadly attended Technology Interchange Meeting (TIM) on CTE-1 technology to 1) assess the state of the art (SOA) and 2) obtain external (industry and other government) inputs on relevant ongoing technology efforts, lessons learned, and recommendations for technology selections (ref. 30). Follow-on meetings were held with interested industrial entities and governmental organizations. Using these inputs to evaluate the current SOA, SNP determined that the current RXS AD^2 was ≥ 4, which strongly suggests that the project should carry more than one reactor design option to reduce development risk. Based on the inputs and the KPPs, SNP SMEs selected three potential space nuclear reactor designs for consideration. The major differentiation between the candidate categories is the strategy employed for heat acquisition and transportation. The options are:

1. High Temperature Gas-cooled Reactor (HTGR) - In this class of reactors, a working fluid consisting of a mixture of helium and xenon (He-Xe) is directly circulated through the core, eliminating the need for a heat exchanger at the reactor/power converter interface. This is a major simplification with respect to other designs. In addition to the elimination of the heat exchanger, the design also eliminates requirements for liquid metal coolant pumping (no liquid metal pump, no separation system, no HP welding, etc.). That said, the containment and circulation of high temperature gases at high pressures while simultaneously achieving low specific weight is a major engineering challenge unique to this design option. Meeting this challenge will require the use of refractory metal alloys. Assuring resilience against single-point failures is also a challenge in NEP HTGR designs - leakage in any part of the coolant piping due to a failed fitting or weld or through micrometeroid damage might compromise overall plant performance. Less challenging but also important, the large thermal gradients typically found in HTGR designs with respect to fuel or moderator temperature requirements must be managed in the cooling design.

2. Heat Pipe-cooled Reactors (HPRs) - NEP reactors in this class employ high temperature alkali-metal HPs to passively transfer heat from the reactor core to the Brayton cycle power converter working fluid through a heat exchanger. Sodium (Na) and Li are typically the candidate working fluids. The NEP HPR design offers low operating pressures, resulting in a low reactor vessel mass with respect to other candidates. It also allows for use of redundant power conversion systems with multiple cross-connects to eliminate single points of failure. A further advantage is that the interface required for testing (on both the reactor and power converter sides) is relatively straightforward and easy to implement. However, there is no existing experience operating a fully commissioned HPR plant. Subscale experimental studies in support of fission surface power (FSP) have been performed, demonstrating the ability to transfer fission heat via a HP over a range of reactor operating conditions (ref. [70]). The major technical challenge at power levels of interest is the complexity of the HP arrangement. Specifically, thermal bonding of the many required HPs to the core and the fabrication of a low specific mass heat exchanger will require focused research and development. At very high temperatures, these systems will likely employ enriched ^{7}Li to reduce parasitic neutron (n) absorption and reduce the generation of radiolytic gasses due to n-interactions with the working fluid. However, the separation of any radiolytic gasses is not difficult in a HP since during operation such components inherently contain both liquid and gaseous media.

3. Liquid-Metal-cooled Reactors (LMRs) - NEP reactors of this type typically incorporate a two-loop design. The primary loop contains a pumped liquid metal (LM) coolant to remove heat from the core. An intermediate fluid-to-fluid heat exchanger is used to transfer heat from the coolant to the secondary power conversion flow loop. Enriched ^{7}Li is typically the liquid metal working fluid option for NEP operating conditions at the projected operating temperatures due to its high boiling point and low neutron absorption cross section. The former prevents phase change during operation and the latter limits undesirable interactions with the neutron population in the core. The major advantage of the LMR concept is the compactness of the core with respect to the HTGR and HPR options. Major LMR challenges include the development of an efficient liquid metal pump, chemical compatibility of the various components with Li, the dynamics and effects of the freeze-thaw process, and generation and potential need to separate of radiolytic gasses due to n-^{6}Li and n-^{7}Li interactions.

A HTGR system was chosen for the Project Prometheus spacecraft (refs. [16, 17]). The SNAP-8, SNAP-10A, SP-100, and all Soviet (BUK and TOPAZ) reactors were LMR-based (refs. [8, 13, 54, 71]). SNP evaluations of the current SOA and development risks posed for each option have resulted in the selection of the HTGR and HPR reactor designs as the candidates to be pursued for the high-power (1-10 $\mathrm{MW_e}$) application. Figure 3.3 illustrates representative reactor cross-sections for the selected options. Major considerations for the selection of the HTGR design were the simplicity and basic design compatibility with the He-Xe mixture to be used as the CTE-2 working fluid (see Section **??**). The selection of the HPR was based on the extensive relevant and ongoing work developing HP-based micro-reactors, including supporting technology development in industry and at the DOE. LMR technology was not selected, and this decision was based on known technical barriers identified in past attempts to develop this type of reactor at the temperatures under consideration (e.g., Li metal pumping systems suitable for high-power, gas generation and separation, chemical compatibility). In addition, there are currently no commercial microreactor designs pursuing LMR technology in applicable temperature range.

While there are many differences, all three NEP reactor options also share important commonalities. Examples of these include:

- Fuel and moderator materials that comprise the reactor core,
- Instrumentation and control (I&C) systems, including the reactor reflector assembly, that assure safe and reliable operation,
- The reactor shielding that protects equipment and humans from radiation emanating from the reactor core,
- Multiple M&S capabilities required to assess performance at the component, major assembly, and CTE levels with respect to specific mass, transient responses at the system level, reliability, and endurance.

Examples of major differences between the different reactor design options include:

- The pressure that the reactor vessel must contain,

- Compatibility between various structural materials and the heat transfer medium,
- The coolant-loop design and various in-core structures that limit the core temperatures to safe levels,
- Thermal management and heat transport technologies, including piping and heat exchangers, that are required to satisfy the system power balance and properly interface with CTE-2.

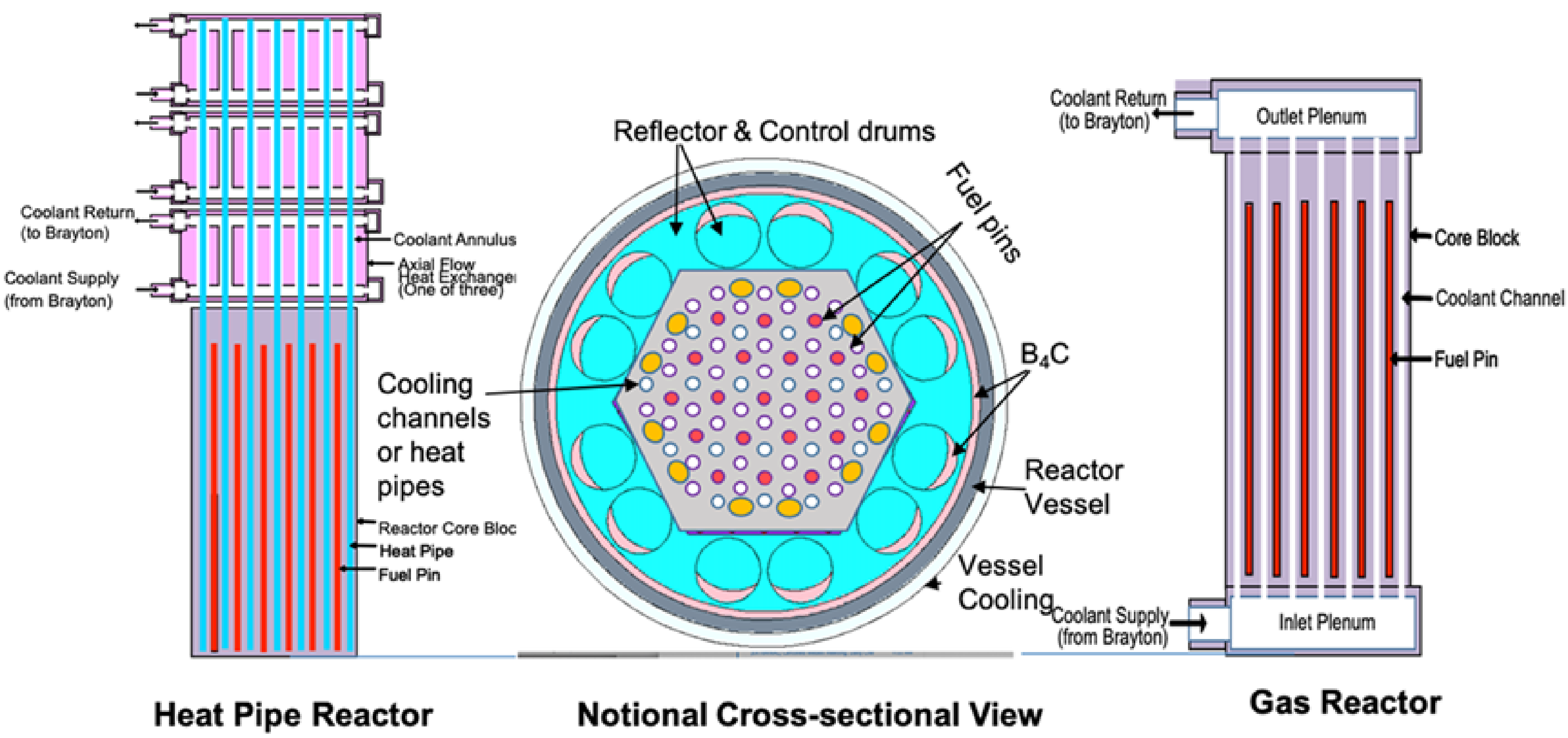


Figure 3.3: A Schematic Representation of a HP reactor and a HTGR.

Tasks are presented in this TMP to advance each selected reactor design. While there are differences between the technologies required for each design, there are also similarities and common advancement tasks that benefit both. The SNP team will direct the technology maturation plans for the NEP reactor to assure project coordination and ensure initial technology development demonstrates or is extensible to the range of operating conditions and geometries expected for each reactor variant. The following sections describe the background, state-of-the-art, and technology gaps for RXS. These lead to milestone-driven CTE-1 technology advancement plans and a risk assessment with corresponding mitigation plans for the top five risks identified for CTE-1 advancement.

3.2 Background, State of the Art, and Technology Gaps

3.2.1 Background: Historic NEP RXS Development Initiatives and Ongoing Advanced Reactor Research and Development Initiatives

NEP reactor technology was first demonstrated for use in space in the 1960s, reaching a zenith in 1965 with the launch of the SNAP-10A reactor, which was the only US reactor ever operated in space (refs. [1, 2, 52]). The SNAP-10A reactor core used highly enriched uranium-zirconium hydride (UZrH) fuel and had a pumped sodium-potassium (NaK) loop for heat transport from the reactor core. Though SNAP development experimented with a variety of reactor operating temperatures and power conversion technologies, the program ultimately settled on a relatively low temperature of roughly 900 K. This reactor generated roughly 500 We using thermoelectric power convertors, and this power was used to operate a cesium-fed (Cs) ion thruster. Subsequent NEP reactor design and technology advancements were intermittent, driven mostly by the SP-100 (refs. [12, 52]) and JIMO projects (refs. [16, 17, 53]). SP-100 was a tri-agency program involving the U.S. Department of Defense (DOD), DOE, and NASA. The program targeted a 100 kW_e space nuclear reactor power system. NEP was one of the mission applications envisioned for SP-100. Significant design, development, and component testing was undertaken, but the project was cancelled before a full reactor system was fabricated and tested. Project Prometheus was initiated in the mid-2000s, targeting a 100 - 200 kW_e NEP system designed for the JIMO mission. The Prometheus Baseline-1 design was a fast-spectrum UO_2 pin-fueled core and employed a direct He-Xe-cooled reactor powering a closed Brayton cycle power conversion system. JIMO was cancelled before any significant component testing or technology maturation was accomplished. These legacy designs and materials focused mostly on HEU with the exception of one DOE sponsored industry and national laboratory study that examined challenges and advantages of using a HALEU-fueled reactor (ref. [72]). Consequently, direct adaption of historic designs to a modern HALEU-fueled NEP RXS may not satisfy the present NEP KPPs.

In 2018, the NASA Space Technology Mission Directorate (STMD) Kilopower project developed, fabricated, and demonstrated a kilowatt-class HEU uranium-molybdenum (U-Mo)-fueled fastreactor core (refs. [56, 57]). This reactor core operated at roughly 1100 K and relied on heat pipes to passively transfer heat to a Stirling power conversion system.

Kilopower development culminated in a reactor experiment known as KRUSTY (Kilopower Reactor Using Stirling Technology) that demonstrated fully integrated subscale (SS) RXS-PCS operation under nominal and selected off-nominal conditions. Given the selected reactor materials, the use of HEU fuel, the PCS employed, and the general small scale of that demonstration, Kilopower technology is not directly adaptable to meet the mission KPPs for a multi-MW NEP system.

On the commercial front, several commercial nuclear companies are developing microreactors to meet the power needs of remote communities and DoD bases (refs. [73, 74]). Although most of the industry design data is proprietary, the following conclusions can be drawn from what is publicly available:

- The industry reactor designs, fuel choices, and power conversion technologies are focused on economically viable modularized reactors in the 1-50 MW_e range. Many of them are planning to use open-air Brayton power conversion systems while a select few are targeting supercritical water and sCO_2 cycles. In general, these systems are significantly different from reactor designs suitable for space power, with the latter focused on size, weight, and control simplicity. A factor of 2 to 3 reduction in specific weight relative to a modularized terrestrial reactor design will be necessary for the NEP mission, which includes a commensurate simplification of the control systems.
- Four reactor vendors are employing HPR designs, with the remaining vendors designing two-loop gas cooled reactors. None of the vendors are investigating LMR designs, with the exception of the Microreactor Application Research, Validation, and Evaluation (MARVEL) at the Idaho National Laboratory (INL), which is planning to use a natural circulation NaK loop for primary heat removal (ref. [55]).
- Most vendors plan to use fuels based upon the Advanced Gas Reactor (AGR) tri-structural isotropic (TRISO) coated particle in an inert high temperature matrix, such as graphite or silicon carbide (SiC). The AGR TRISO is a specific coated particle fuel design which has received significant investment from the DOE under the AGR program. Work has been performed to qualify the fuel form for specific reactor applications and the coated particles have well understood performance with well-developed fabrication, and quality control techniques (refs. [75, 76]). To further improve economic viability, there are plans to ultimately move toward higher density micro-engineered particles or encapsulated pellets, which may result in significant changes to the fabrication process parameters and fuel performance compared to AGR TRISO (ref. [77]). The DOE's Office of Nuclear Energy has funded the Advanced Reactor Demonstration Program (ARDP) and risk reduction efforts to explore microreactor designs based on reactors using higher density fuels (refs. [55, 75, 76]).

3.2.2 State of the Art Summary

The present state of readiness for reactors of relevance to NEP can be summarized as follows:

- HTGR, HPR, and LMR NEP reactors all have relative advantages and unique challenges. Numerous past studies as well as ongoing point-design assessments have established that reactor specific mass is not a major discriminator among these concepts (that is, all three designs result in approximately the same specific mass after accounting for total system performance and mass). ***None of the options possess a high technology readiness level that would support an informed down-select decision at this time***; but HTGRs and HPRs have lower AD^2 compared to LMRs. Although lithium-cooled LMRs for NEP applications achieved a relatively high TRL at some point in the past (ref. [78]), development was terminated well before they achieved nuclear qualification and the technology base no longer exists. The highest TRL/lowest AD^2 systems are the HPR and HTGR concepts, which will be pursued through the balance of this TMP.

- Most of the recent progress on key components, such as nuclear fuels, high temperature moderators, and other in-core materials, as well as instrumentation, has been achieved for use in thermal spectrum reactors. For example, the DOE accident tolerant fuels (ATF) initiative is advancing the technology base for high performance fuels and radiation tolerant ceramic cladding for use in thermal spectrum reactors. Many of these fuels could be adapted for NEP application with a focused development program because NEP nuclear and non-nuclear environment conditions are similar to those of terrestrial reactors. ***Reactor facilities required for developing and verifying the performance of thermal spectrum reactor components already exist.***

- At present two US companies, TerraPower and Oklo are pursuing fast spectrum reactors for commercialization. Neither the fuel (uranium-zirconium metal alloy) nor the operating temperature (800-900 K) is extensible to a high-power NEP mission. Fast spectrum reactors capable of meeting NEP missions are likely to require high temperature ceramic fuels clad in refractory alloys. US or Organization for Economic Co-operation and Development (OECD) countries currently possess extremely limited test facilities to qualify such materials and obtain the design data. Furthermore, a HALEU based fast-spectrum reactor does not offer mass or size advantage. For these reasons, fast spectrum reactors shall not be considered or revisited unless it is determined at some point by NASA that use of HEU is necessary to conduct high-power NEP missions.

- DOE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program is advancing a multi-scale and multi-physics modeling environment that could be directly leveraged for NEP use (refs. [78, 79]). Use of this physics-based high-fidelity modeling environment approach could accelerate reactor development (refs. [80, 81, 82]).

- Joint DOE, DOD, and industry investment into Gen IV small- and micro-reactor development is addressing some of the key development and demonstration gaps for HTGRs and HPRs operating on a thermal neutron spectrum. Proposed activities under DOE's ARDP and other US initiatives are recapturing some of the mothballed technology base and infrastructure for demonstrating NEP-size reactors. Examples of needed facilities include:
  - Critical facilities required for reactor physics model validation and understanding of dynamic reactor response,

  - I&C laboratory infrastructure required for verifying and validating advanced control architectures,
  - Test facilities for full-power ground nuclear demonstrations.

The basis for reactor development is given in the balance of this chapter, where specific tasks required for technology maturation are described. It is important to note that not every technology gap needs to be overcome by the SNP NEP project. In many cases, ongoing reactor projects are already tackling some of the critical challenges. A key to success is to align NEP development with other ongoing efforts. Table 3.2 compares NEP operating conditions and potential design options with other ongoing US programs. Given this interplay, the CTE-1 reactor is baselined to be a thermal spectrum reactor that will benefit from, and will be of benefit to, other US nuclear reactor research programs. Alignment with ongoing DOE microreactor, NEAMS, and ARDP initiatives is strongly recommended to minimize project risk and maximize return on investment. SNP plans to establish a forum for internal and external project information exchange of ongoing advancement activities to ensure open communication between various ongoing technology development efforts in the nation.

Table 3.2: Comparison of proposed NEP operating conditions and potential technology options with ongoing DOE and NASA Reactor Development Programs. (Blue (*), green (**) and purple (†) entries, respectively, denote technologies that are likely to be developed by DOE microreactor, FSP and NASA SNP (NTP) programs, respectively; orange (‡) entries denote incremental research and development being proposed for the NEP development activities under the SNP project. LWR – light water reactor.)

Major Technology Parameter	**Microreactors**	**FSP**	**Nuclear Electric Propulsion**	**Nuclear Thermal Propulsion**
Power output	1-10 MW$_e$	$>$ 40 kW$_e$	1-4 MW$_e$	100s of MW$_{th}$
Operating time (effective full power)	Up to 10 years	7-10 years	2-4 years	$<$ 1 day
Process heat temperature	900-1100 K	~1000 K	Target 1400 K / Minimum 1200 K	2800 K
Key nuclear characteristic	Thermal spectrum. Burn-up limited.	Neutron spectrum TBD. Criticality limited.	Thermal spectrum. Burn-up limited.	Thermal spectrum. Heat-transfer limited.
Power density	~100s watts/cc	~10s watts/cc	~100s watts/cc	$>$ 5000 watts/cc
Fuel type / form	TRISO*, FCM*, Ceramic (UO$_2$ and UN) pellets*, UMo and UZr fuels*	TBD (mostly leverage DOE fuels research and development)	TBD UO$_2$/UN pellets‡ or micro-engineered fuel)	UN micro-engineered particles† (or) Mixed carbides†
Reactor coolant	Gas flow* or Na/K-HP; Test facility*	Na/K-HP** and HeXe are the leading candidates	Li-HP‡ and He-Xe‡ are leading; Pumped Li being assessed	LH$_2$
Moderator	Graphite* or yttrium- and zirconium-hydride*	Long-duration hydride for thermal spectrum**	Yttrium hydride** or BeO (long-duration at high temperature)‡	Hydride† or Be compounds† (short duration at power)
Neutron reflector	Graphite or BeO	Be or BeO		
Shielding	Traditional shields (water, concrete etc.)	Light weight surround shield**	Light weight high temperature directional shield†	
Structural materials	Graphite, SiC composites* and superalloys*	TBD (Superalloys and SiC-composites)	Graphite‡, ceramic-composites†, refractory alloys‡	

Table 3.2: Comparison of proposed NEP operating conditions and potential technology options with ongoing DOE and NASA Reactor Development Programs. (Blue (*), green (**) and purple (†) entries, respectively, denote technologies that are likely to be developed by DOE microreactor, FSP and NASA SNP (NTP) programs, respectively; orange (‡) entries denote incremental research and development being proposed for the NEP development activities under the SNP project. LWR – light water reactor.)

Major Technology Parameter	**Microreactors**	**FSP**	**Nuclear Electric Propulsion**	**Nuclear Thermal Propulsion**
Instrumentation & control	Standard LWR instruments (research and development into fiber optic-based systems)	TBD (FSP I&C for continuous power reactor application**; Adapt past space qualified nuclear reactor instrumentation (SP-100/SNAP Pedigree)‡)		TBD
Modeling & simulation	NEAMS tools exist for integrated reactor system M&S*. Also qualified commercial and university tools with multi-decadal pedigree exist.			TBD
Industry fuel research & development, fabrication, and assembly lines	DOE ARDP for TRISO DOE ATF for ceramic pellets	Exists for HALEU (NNSA/Industry Infrastructure)	Industry procured‡ or use NTP fuel line†	Need new nuclear facilities
Ground test facilities	Existing EIS and NEPA at two DOE sites. Will need facility modification for full power testing. NRIC/DoD investments to increase capacity.*			Need new EIS, NEPA authorization and new one-of-a-kind facilities

3.3 RXS Component Technology Options

Pre-conceptual point designs, representative of direct gas-cooled, liquid metal HP, and pumped LMR options, were developed to identify alternative technologies, materials, and components that are likely to achieve SNP KPP minimum values. These designs were not 'nuts-and- bolts' level detailed designs but were instead developed to a level of detail sufficient to draw insights regarding feasibility of each option and to develop mass estimates. Figure 3.4 illustrates important components of a notional direct He-Xe gas cooled reactor design excluding directional shield. Most of these components (for example, fuel, moderator, and reflector), are common to all three design options and are subject to similar operating conditions. The significant differences between the design options are:

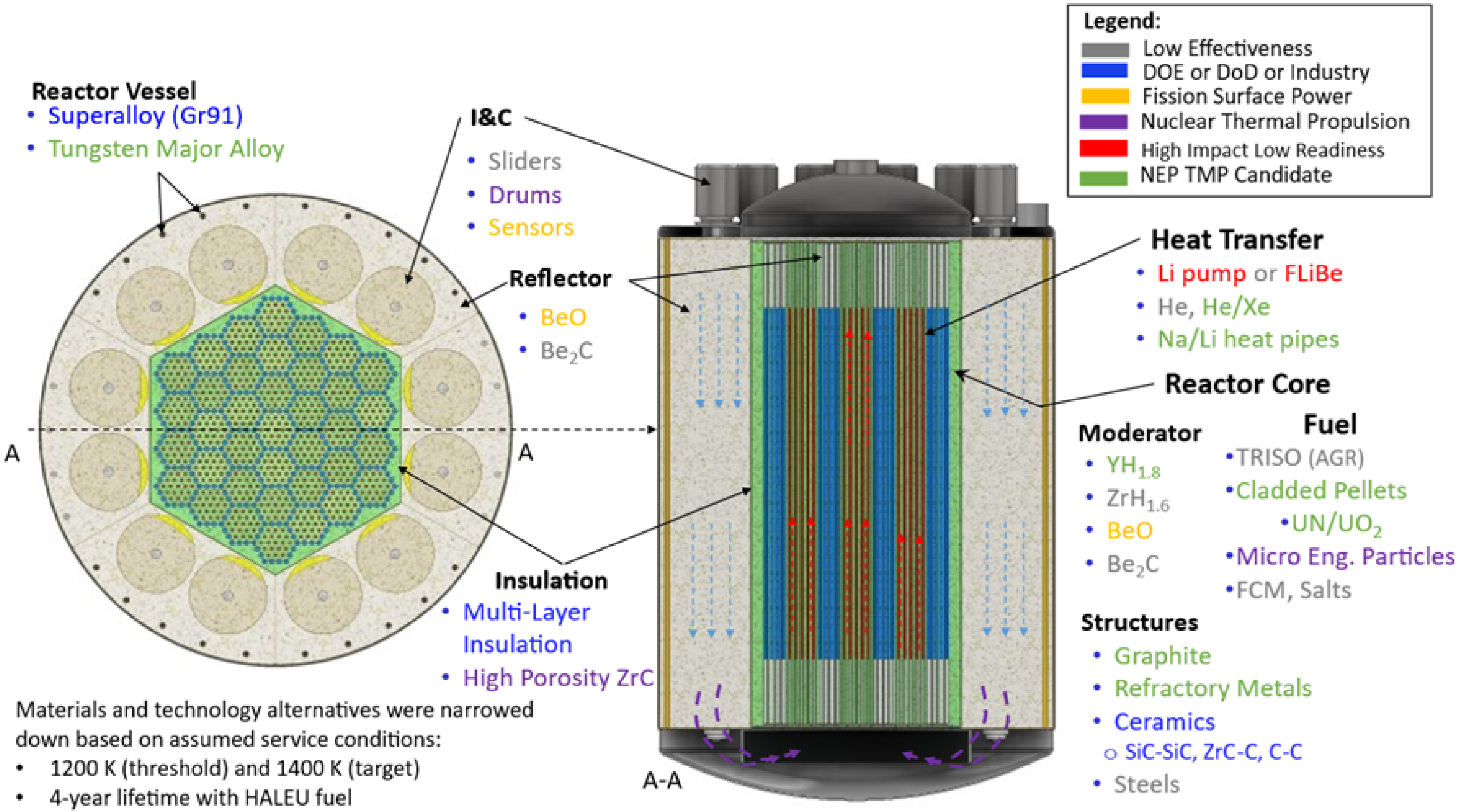
- HPRs rely on high throughput Li HPs for heat transfer from the core to the heat exchanger. While such heat-pipe assemblies have been demonstrated, thermally bonding them to the core and to heat exchanger elements has not been demonstrated at the MW_{th}-scale.
- In direct HGTRs, reactor vessel and coolant piping are simultaneously subjected to high pressures and temperatures necessitating vessel wall cooling (if superalloys are used) and/or the use of refractory metal alloys. Design features necessary to eliminate potential for single-point failures can add to further fabrication complications.
- Li-cooled LMRs rely on an external pump to circulate enriched liquid ^{7}Li through the core. A pumped Li loop must be designed to handle phase change ($T_{\text{melt}} \sim 453$ K, $T_{\text{boil}} \sim 1615$ K) and to separate gases generated by radiolytic reactions from the pumped liquid. Repeated efforts to fabricate and qualify pumped Li loops have fallen short of minimum component performance goals such as pumping efficiency and reliability. Technology for separating radiolytic-generated He gas from flowing liquid lithium in zero-g was never successfully demonstrated.

Despite these differences, the preliminary conclusions are that: (a) all three design options result in about the same CTE-1 mass and (b) a common set of material and technology combinations can be employed to achieve KPPs for all three options. Based on internal modelling activities and industry inputs, an extensive – but not necessarily complete – list of materials and technology candidates were identified and are listed for key components in Figure 3.4 Where necessary, further parametric analyses were carried out to examine size, mass, and performance implications for each of the materials or technologies (refs. [22, 83]). Due to the wide design space identified, only a subset of these technologies (shown in (***green text***) in Figure 3.4) are specifically addressed within this TMP. However, the overall task plan may still be applied if an alternative technology was selected. The three criteria used to narrow down the materials and technology choices considered for technology maturation.

1. Excluded from this TMP are those options that are unlikely to achieve KPPs without significant investments, are likely to result in low margin (risky) nuclear designs, or that are unique offerings of a particular company. These include AGR TRISO and molten salt fuels, and zirconium hydride ($ZrH_{1.6}$) and beryllium carbide (Be_2C) moderators.

2. Also excluded from this TMP are those options that are important but are being pursued by the ongoing research and development in other DOE (***blue text***), FSP (***orange text***) and/or NTP projects (***purple text***). Superalloy based piping/structures and heat exchangers, microengineered particle fuels and zirconium carbide (ZrC) insulation are some of the examples of development activities from other programs that could be coordinated with and infused into NEP technology advancement efforts.

3. Options included in this TMP but may be pursued via alternative investment strategies are those likely to have high impact if matured to the deployment stage, but that presently possess low technology and manufacturing readiness. Two important examples are pumped Li and pumped lithium beryllium fluoride (FLiBe) molten salt technologies.



Materials and technology alternatives were narrowed down based on assumed service conditions:

- 1200 K (threshold) and 1400 K (target)
- 4-year lifetime with HALEU fuel

Figure 3.4: Schematic representation of a notional He-Xe direct gas cooled reactor. Legend colors refer to text colors. Candidates selected (*green text*) were the result of TIM and industry input.

3.4 RXS Technology Advancement Plans

This section outlines the SNP approach to the development of RXS (CTE-1) technologies planned to advance readiness from its current status to TRL 5 after a 4-year program. In this plan, candidate technologies and a summary of corresponding technology development steps is identified in Table 3.3.

Table 3.3: CTE-1 Major Technology Aspects and Advancement Requirements.

	Technology Description	**Technology Options**	**Advancement Descriptions**
1	Fuel	UO_2, uranium nitride (UN) fuel pellets stacked in a compatible cladding tube	Demonstrate/confirm fuel rod performance through mechanical, thermal and irradiation testing of UO_2 and UN fuel to achieve TRL-5. Assess infrastructure investments required for manufacture of prototypic scale fuel assemblies. Use test data to validate state-of-the-art models. Collect as fabricated and irradiated material properties to close any knowledge gaps.
		"micro-engineered particle" composites (backup option)	Micro-engineered particle fuel option will be carried forward to mitigate potential risk that pellet based high density fuels might not perform as expected. It will primarily rely on the NTP project investment into micro engineered particles.
2	Moderator	Yttrium Hydride (YH_x) moderator with hydrogen barrier coatings/clads	Demonstrate/confirm net-shaped moderator assembly performance through mechanical, thermal and irradiation testing to achieve TRL-5. Use test data from the testing program to modify and validate hydride moderator models to project performance at target operating conditions.
		Beryllium Oxide (BeO) or other Be-compound	Confirm net-shaped moderator assembly performance through thermal and irradiation testing to achieve TRL-5. Use test data from the testing program to validate predictive models for swelling/dimensional change behavior under high temperature irradiation.

Table 3.3: CTE-1 Major Technology Aspects and Advancement Requirements.

	Technology Description	**Technology Options**	**Advancement Descriptions**
3	Cladding / Coatings	Refractory Metals (molybdenum, Mo; molybdenum-tungsten, MoW; tungsten, W)	Demonstrate feasibility of a radiation tolerant coating/cladding system that acts as barrier against working fluid interactions and fission product release. Use the clad in fuel and moderator tests described above and in the assembly demonstration. Utilize the test results to validate the hydrogen and fission product permeation models for clad and coating designs. Demonstrate the ability of the cladding to exhibit acceptable creep behavior.
		Ceramic Composites (C_f-C, SiC_f-SiC, C_f-ZrC)	Demonstrate manufacturability of composite tubing including any required coatings to ensure hermiticity or chemical compatibility with working fluid or fuel. Extend material property database if gaps exist. Demonstrate feasibility of composite cladding under relevant laboratory conditions described in the refractory metal cladding advancement description.
4	Insulation	Multi-Layer Insulation (MLI)	Demonstrate acceptable sustained performance of high-performance insulation in long duration testing under relevant thermal and nuclear environments.
		SiC/ZrC High Porosity Insulation (leverages NTP research)	Demonstrate the ability to manufacture insulation that meets thermal properties and net-shape geometry specifications. Demonstrate acceptable sustained performance of high-performance insulation in long duration testing under relevant environments.
5	Heat Transfer (HPR only)	Mo-HP assembly with finned condenser	Demonstrate a high throughput Mo-alloy based HP with finned surfaces for enhanced heat transfer through integral testing including in nuclear environment. Use test data from the testing program to modify and validate the heat transfer models to project HP performance at target operating conditions. Demonstrate HPR and heat exchanger assembly techniques.

Table 3.3: CTE-1 Major Technology Aspects and Advancement Requirements.

	Technology Description	**Technology Options**	**Advancement Descriptions**
6	Pressure vessels (HTGR only)	Superalloy or Tungsten Major Alloy	Manufacture an actively cooled flight-like high-pressure reactor vessel capable of supporting He-Xe at 2-6 MPa while at 1200 K (superalloy) or 1400 K (tungsten major alloy) during Phase 1. Use test data and validated structural mechanics tools to project performance at target operating conditions and develop design limits. Demonstrate resilience of the component against potential meteor strikes and ability to operate under off-nominal operating conditions.
7	Reflector Assembly	Beryllium oxide (BeO) reflector & drums	Establish/confirm readiness of BeO reflector and drums making use of data from DOE (MARVEL), NASA's NTP and FSP Projects. Limited research and development is expected.
8	I&C	Radiation-tolerant sensors, circuits, relays, and actuators to required functionality	Demonstrate fault-tolerant and uninterrupted performance of a control architecture through a combination of M&S and component testing. Consider impact of space environment and reactor neutron and gamma field on sensor operation. Perform confirmatory irradiation testing if irradiation performance data gaps exist.
9	Fuel Assembly and Core Structures	Fuel 'assembly' and core structures constructed of mechanically robust, creep- and corrosion-resistant materials	Demonstrate a fabrication-ready fuel 'assembly' structure through thermo-mechanical testing, neutronic reactivity measurement, and finally irradiation in a reactor core to the required burnup level (or displacements per atom, dpa). Use test data from the testing program to modify and validate structural analysis models (e.g., NEAMS) to project mechanical performance at target operating conditions. Incorporate fuel assembly structures into planned TRL-5 demonstration activities.

Table 3.3: CTE-1 Major Technology Aspects and Advancement Requirements.

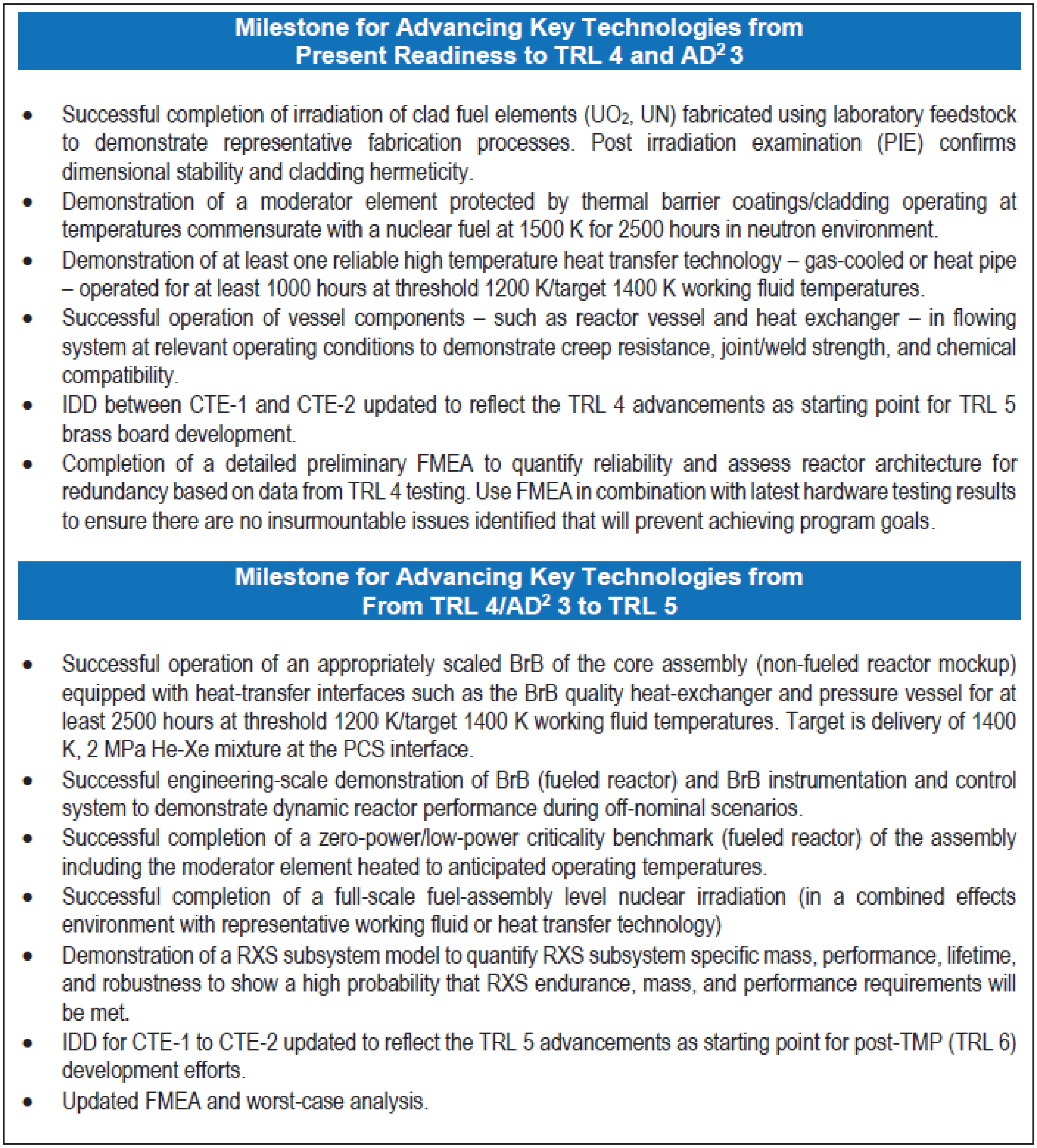
	Technology Description	**Technology Options**	**Advancement Descriptions**
10	M&S	Integrated RXS-system model capable of predicting NEP system performance	Modify existing models to demonstrate a NEP RXS subsystem and component models that predict (to the desired degree of fidelity) sub-system α and performance during nominal and off-nominal operating conditions. Use test data from hardware testing tasks to validate model predictions and to quantify modeling uncertainties.

What follows are component level technology advancement tasks recommended to improve RXS component technologies to TRL 5 in advance of an integrated TRL 5 RXS brassboard (BrB) demonstration. Component level technology advancement is described for the baseline candidate technologies identified in Figure 3.4. Each plan includes design, fabrication, and testing activities to demonstrate component maturity at the appropriate level of fidelity to support technology maturation and down-selects between options. Each testing task is preceded by a testing readiness review (TRR). Upon completion of a test, a task completion review (TCR) and model validation review (MVR) are scheduled to confirm testing objectives have been met and data collected from the test are understood and validated using existing models and/or the data are used to improve modeling capability. Following completion of all planned advancement activities for a given TRL/AD^2, a NAR is planned to allow for an independent assessment of whether advancement objectives have been met for the component.

The component advancement descriptions are intended to provide a prescriptive level of detail that captures the critical testing parameters and technology gaps to be addressed in NEP RXS technology advancement. However, it is recognized that alternate component design options may be implemented or eventually supersede the candidates described in this TMP. These components would need to meet a commensurate level of design, fabrication, and testing fidelity (for both the test articles and test environments) and to demonstrate performance as well as conduct a TRR and TCR/MVR for each planned test or advancement. If during development work it becomes possible to down-select between the various candidate component options, it is recommended these down-selections be performed after completion of major review milestones, such as the TRL advancement NARs. In addition to alternative candidates, there exist component candidates before which development is planned in coordination with external project partners. These components should be treated similarly, with the planned development activities being consistent with the required level of fidelity and tested in the specified environments to meet this plan's TRL/AD^2 advancement criteria. The developments and test results should also be independently assessed by NAR to assure advancement in maturity. All components selected or required for the RXS BrB are expected to satisfy the component level TRL 5 NAR and must be demonstrated (through analysis and/or testing) to be capable of meeting subsystem-level interface requirements.

This subsection the proceeds with an overview of the RXS subsystem and subassembly level testing recommended to improve the overall RXS subsystem readiness to TRL 5/AD^2 2. This strategy leverages a sub-scale (SS) BrB of the RXS subsystem to provide the test data necessary to validate reactor thermal, structural, and nuclear models, and develop experience operating instrumentation and control systems in a reactor environment. The work also demonstrates the capability of the matured design to meet desired performance parameters and functional characteristics of the system. This is followed by details on M&S tasks required for RXS maturation. Schedules related to planned advancement tasks are included in the tables throughout this section. A summary of key milestones for improving reactor technology readiness to TRL 4/AD^2 3 and TRL 5 is captured in Figure 3.5.

The proposed schedule is a methodical but success-oriented, allowing for rapid component level and subsystem development and demonstration to TRL 5 by the end of the fourth development year. This is enabled by pursuing the development of critical technologies in parallel for technology advancement tasks up to TRL 4/AD^2 3 and TRL 5 and identification of critical decision points to down-select between the candidate technologies. This would typically occur after completion of a specific milestone demonstration activity or non-advocate TRL advancement review. The schedule will be delayed should any technology require unplanned iterative development and testing. The identified schedule assumes a set of reference technologies as outlined in this TMP, however alternative technologies may also be considered if they meet the intent of the prescribed technology advancement tasks. NAR milestones may be used to evaluate whether alternative technologies meet the readiness criteria and are at a level where they may be successfully integrated with other reference reactor technologies. Lastly, the schedule assumes the readiness and availability of required facilities by the anticipated need date. Lack of suitable facilities may delay the schedule, limit the achievement of test objectives, reduce the fidelity in test conditions, or constrain the design of test articles. Facilities development or modification is included in the schedule for RXS BrB testing. However, the TMP development plans do not address required test objectives, critical test environments, test article design, and facility readiness for component-level testing. Top risks for CTE-1 technology development are identified in Section 3.5.



**Milestone for Advancing Key Technologies from
Present Readiness to TRL 4 and AD^2 3**

- Successful completion of irradiation of clad fuel elements (UO_2, UN) fabricated using laboratory feedstock to demonstrate representative fabrication processes. Post irradiation examination (PIE) confirms dimensional stability and cladding hermeticity.
- Demonstration of a moderator element protected by thermal barrier coatings/cladding operating at temperatures commensurate with a nuclear fuel at 1500 K for 2500 hours in neutron environment.
- Demonstration of at least one reliable high temperature heat transfer technology – gas-cooled or heat pipe – operated for at least 1000 hours at threshold 1200 K/target 1400 K working fluid temperatures.
- Successful operation of vessel components – such as reactor vessel and heat exchanger – in flowing system at relevant operating conditions to demonstrate creep resistance, joint/weld strength, and chemical compatibility.
- IDD between CTE-1 and CTE-2 updated to reflect the TRL 4 advancements as starting point for TRL 5 brass board development.
- Completion of a detailed preliminary FMEA to quantify reliability and assess reactor architecture for redundancy based on data from TRL 4 testing. Use FMEA in combination with latest hardware testing results to ensure there are no insurmountable issues identified that will prevent achieving program goals.

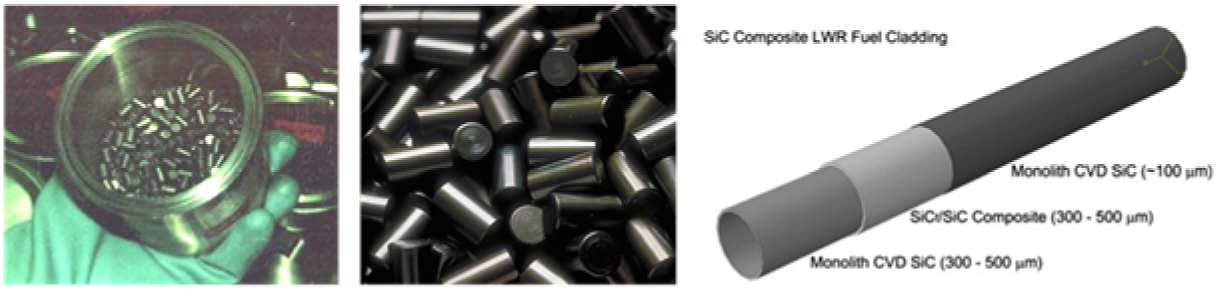
**Milestone for Advancing Key Technologies from
From TRL 4/AD^2 3 to TRL 5**

- Successful operation of an appropriately scaled BrB of the core assembly (non-fueled reactor mockup) equipped with heat-transfer interfaces such as the BrB quality heat-exchanger and pressure vessel for at least 2500 hours at threshold 1200 K/target 1400 K working fluid temperatures. Target is delivery of 1400 K, 2 MPa He-Xe mixture at the PCS interface.
- Successful engineering-scale demonstration of BrB (fueled reactor) and BrB instrumentation and control system to demonstrate dynamic reactor performance during off-nominal scenarios.
- Successful completion of a zero-power/low-power criticality benchmark (fueled reactor) of the assembly including the moderator element heated to anticipated operating temperatures.
- Successful completion of a full-scale fuel-assembly level nuclear irradiation (in a combined effects environment with representative working fluid or heat transfer technology)
- Demonstration of a RXS subsystem model to quantify RXS subsystem specific mass, performance, lifetime, and robustness to show a high probability that RXS endurance, mass, and performance requirements will be met.
- IDD for CTE-1 to CTE-2 updated to reflect the TRL 5 advancements as starting point for post-TMP (TRL 6) development efforts.
- Updated FMEA and worst-case analysis.

Figure 3.5: Key Milestones in the CTE-1 RXS Advancement Strategy.

3.4.1 Fuel

The primary function of the fuel element (FE) in the NEP RXS subsystem is to generate fission heat at a volumetric density and temperature sufficiently high to meet thermal power and power conversion inlet temperature (PCIT) requirements. Therefore, the fuel form in the NEP system must be capable of high performance and reliability at the NEP system operating conditions. UO_2 or UN pellets clad in advanced claddings such as refractory metal tubing or ceramic composites, such as carbon-carbon fiber composites (C_f-C) or silicon carbide-silicon carbide fiber composites (SiC_f-SiC) (Figure3.6), are described in this section as the reference candidate fuels for NEP technology advancement. SNP will work with industry, the DOE, and NASA personnel to incorporate alternative candidate fuel data as appropriate.



(a) SP-100 UN Pellets (b) Commercial UO_2 Pellets (c) ATF SiC-SiC cladding options

Figure 3.6: Examples of pellet-rodlet fuel types baselined for the NEP RXS.

Past space power reactor programs have pursued technology development of UO_2 and UN fuels for space applications. However, each fuel type in these past programs has not reached the readiness to be considered fully matured for crewed NEP applications. Terrestrial programs have also developed these fuel types primarily for light-water reactor (LWR) and LMR applications at lower working fluid operating temperatures (which affects cladding selection and performance) and different working fluid types. A summary of existing UO_2 and UN irradiation performance data is included in Table 3.4. Due to the large existing database, TRL 4 and 5 fuel maturation activities would focus on confirmatory testing with NEP specific fuel materials and geometries, allowing for validation of predicted fuel performance behavior (based on existing database) and closure of key knowledge gaps. At present the following knowledge gaps relevant to NEP applications have been identified for these fuel forms: confirmation of unirradiated material properties at high temperatures (fuel centerline temperatures > 1500 K), validation of irradiated material behavior including dimensional stability (fuel swelling and cladding creep) for the exact fuel chemistries/material systems and geometries fabricated for NEP reactor designs, quantification of fission product-cladding interactions and fission gas release at NEP temperatures and burnup levels, and identification of production scale manufacturing techniques and facilities for fuel fabrication at the scale required for a demonstration reactor (BrB) and full-scale (FS) operational system.

Table 3.4: Comparison of the Existing Fuel Performance Database for UO_2 and UN Fuel Forms to NEP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	**Working Fluid / Heat Transfer Interface**	**Interfaces**	**Power Density (W/cm^3)**	**Lifetime (or Burnup)**	**Reactor Operations**
NEP Reference	1300-1700	He-Xe or HP	Refractory Metal or Ceramic Composite Cladding	≥100	5 yrs	-
			Existing UO_2 Performance Database			
LWRs	Varies: >1473	H_2O	Zr-alloy Cladding	55-90	years	Yes
LMRs	Varies: >973	Na	Steel Cladding (most common)	3.5-133	years	Yes
SP-100	1000-2200	Li	Nb-1Zr Cladding	not reported	months (≤6% FIMA)	No (EBR II irradiation experiments only)
Thermionic Fuel Element Verification Program (TFEVP)	1700-1950	-	W, Nb	not reported (2-6 W/cm^2)	≤13,500 hr (0.07 - 1.4% FIMA)	TOPAZ Reactor Experiments performed within the US
			Existing UN Performance Database			
LMRs	<1023	Na and Pb	Steel Cladding	3.5-133	years	No
SNAP-50	>1263	Li (He Gap)	Nb-1Zr alloy Cladding	not reported	1150-13000 hours	No
SP-100	1100-2100	Li	PWC-11 Cladding (with W or Re liner)	not reported	7 years (4.5% FIMA)	No

Table 3.4: Comparison of the Existing Fuel Performance Database for UO_2 and UN Fuel Forms to NEP Application Fuel Performance Parameters

	Peak Fuel Temperature (K)	**Working Fluid / Heat Transfer Interface**	**Interfaces**	**Power Density (W/cm^3)**	**Lifetime (or Burnup)**	**Reactor Operations**
NASA Lewis Compact Reactor	1103-1263	Li	T-111 Cladding	not reported (2.8×10^{14} n/cm^2s)	(Up to ~1% FIMA)	No

The NEP fuel technology advancement tasks tackle these gaps systematically by focusing on the demonstration of robust fuel performance and manufacturing methods under increasingly more representative operating conditions and geometries (Table 3.5 and Table 3.6; Figure 3.7). To refine identified knowledge gaps and design specific challenges, a phenomena identification and ranking table (PIRT) workshop is planned as the initiating task to (a) identify relevant materials challenges and applicable failure modes; (b) assess how proposed planned testing task objectives will allow for the fuel performance quantification, including margin to failure. Bounding environmental conditions to which fuel may be subjected to will be determined from the failure modes and effects analyses executed in parallel. References [80, 81, 82, 84, 85] provide an extended rationale for the fuel maturation tasks described below. The purpose of the NEP fuel development plan is to ready fuel to a maturity that enables the fabrication of a BrB reactor and allows SNP to make programmatic decisions and technology down-selections. It is expected that there will be preparatory steps between each milestone that are not included in the presented schedules.

Table 3.5: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
PIRT Workshop	CTE1-1.1	Q1/Y1	Phenomena Identification and Ranking Table is a structured approach for SME review of fuel, materials and reactor relevant phenomena and possible failure mechanisms to inform specific objectives and demonstration criteria for fuel development. Identified development activities will aim to establish a range of specific testing conditions and model advancement goals for the TMP. SME's will include representatives from academia, NASA, the national laboratories, and industry. Decision point: SMEs identify uncertainties that may not be resolvable by within the 4-year development program. PIRT review may result in revision of fuel or cladding choices. SMEs will identify reliability and performance goals for reference fuel system types to refine objectives and acceptance criteria for all fuel development tasks.
Design FE pellets	CTE1-1.2	Q3/Y1	This step includes all design and analysis activities to support fuel technology advancement tasks in this table. Component level design activities should be traceable to subsystem and system level modeling and simulation efforts.
Fabricate FE pellets using laboratory feed stock	CTE1-1.3	Q4/Y1	This step resolves uncertainty related to manufacturability of thin pellets fuels and claddings baselined for NEP. Pellet diameter impacts fuel performance (fuel swelling and temperature gradients). Decision point: Fuel pellets of the proposed size and shape manufacturing reliability. Larger pellet size may necessitate use of UN instead of UO2 to avoid large thermal gradients within the fuel. Following pellet fabrication demonstration, demonstrate manufacturability of corresponding cladding or coating technologies if applicable.
Material Property Test Series	CTE1-1.4	Q1/Y2	Gather material properties of as-fabricated fuels and claddings if material property gaps exist.

Table 3.5: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
FE Non-Nuclear Environments TRR	CTE1-1.5	Q3/Y1	Perform a peer review of the 1000-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures. Final down-select between UN and UO_2 pellet options can be made based upon the outcomes. This may correspond to down-selection of subcomponent material technologies in other fuel designs.
Clad and seal FE pellets into a robust rodlet assembly	CTE1-1.6	Q1/Y2	Using established fabrication processes, clad and seal pellets into a robust representative fuel assembly in preparation for 1,000-hour non-nuclear environments testing.
Perform non-nuclear FE environments testing	CTE1-1.7	Q2/Y2	Perform non-nuclear environments testing under laboratory non-nuclear environments for up to 1000 hours. This step resolves two uncertainties: (1) do the rodlets need additional structural reinforcement and (2) are they leak-tight following thermal/mechanical cycling. The latter characteristic may not be important for space application but could complicate ground testing. Demonstrate cladding - pellet performance under a relevant non-nuclear environment (representative temperatures and durations; optional: working fluid interface for direct gas and pumped liquid metal cooled reactors) Decision point: Assess need for grid-plates or bracing and related impacts on ground demonstration design using multiphysics models. Confirm compatibility of cladding-pellets, cladding hermeticity, and cladding-working fluid compatibility.
FE non-nuclear post-test evaluation	CTE1-1.8	Q2/Y2	Perform initial post-test evaluation to confirm integrity of fuel and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to irradiation testing.

Table 3.5: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
1000-hour non-nuclear FE environments TCR & MVR	CTE1-1.9	Q1/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met and that proceeding with irradiation testing is appropriate. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
2500-hour FE Preliminary Irradiation Campaign TRR	CTE1-1.10	Q4/Y1	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
FE Preliminary Irradiation Testing Campaign	CTE1-1.11	Q2/Y2	This step establishes feasibility of NEP HALEU fuel designs by addressing major technical risks: (1) dimensional stability of the fuel element and (2) swelling and fission gas release does not exceed model predictions or require change in design to mitigate. This testing also will provide safety data in support of follow-on nuclear tests and ground demonstration.
FE Preliminary Irradiation Testing post-test evaluation	CTE1-1.12	Q2/Y2	Perform initial post-test evaluation to confirm integrity of fuel and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to TRL 5 technology advancement tasks.

Table 3.5: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	#	**Timeframe (End Date)**	**Significance**
2500-hour Fuel/Moderator Preliminary Irradiation Campaign TCR & MVR	CTE1-1.13	Q2/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues. Decision point: Assess need for any modifications such as increased gap side and/or cladding thickness. May necessitate modifications to the design (e.g., lower power density or lower operating temperature). Gross failure will require pursuit of alternative fuel forms, such as particle fuels which are generally associated with higher α.
TRL/AD^2 Advancement NAR	CTE1-1.14	Q2/Y2	Peer-evaluation to evaluate whether the fuel material system and related modeling efforts have met all goals specified for advancement to TRL 4 and AD^2 3. Down-selection of alternative fuel component designs may be completed at this step.

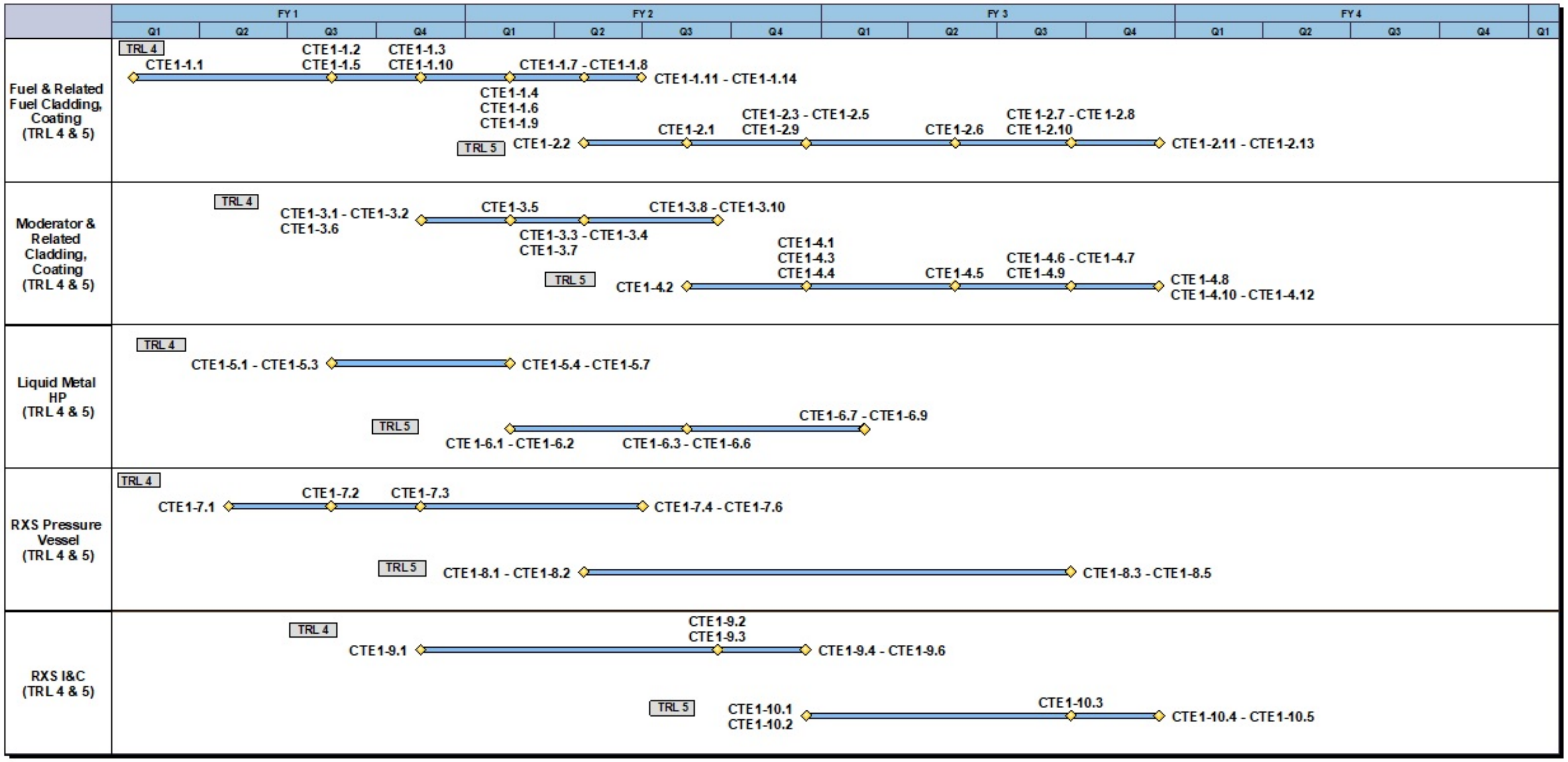


Figure 3.7: CTE 1 Advancement Schedule (tasks CTE1-1 through CTE1-10)

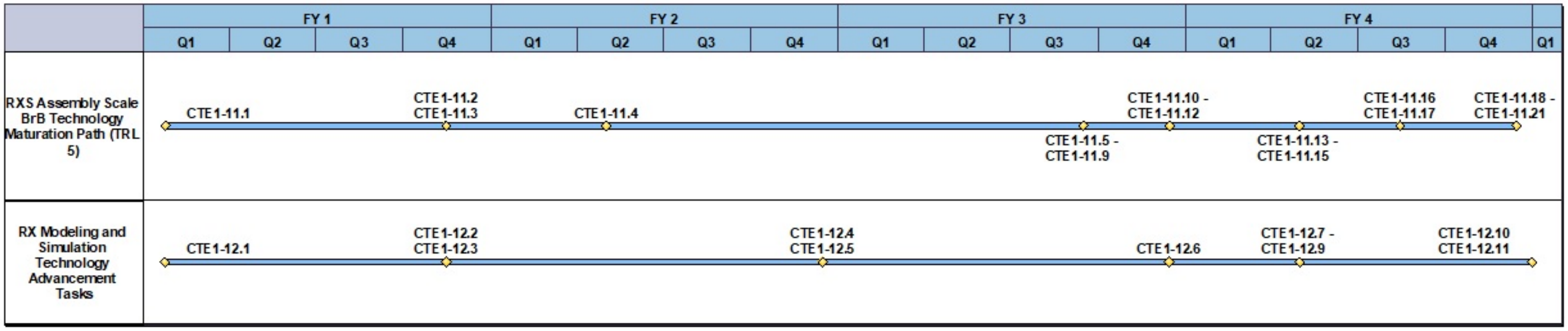


Figure 3.8: CTE 1 Advancement Schedule (tasks CTE1-11 through CTE1.12)

Table 3.6: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Develop test plan for irradiation campaign	CTE1-2.1	Q3/Y2	Reconvene PIRT panel to assess need for and scope of additional testing. SME review of the fuel element designs prior to initiation of fabrication by industry - PM approval for fabrication to proceed. Decision point: Single element burn-up and irradiation test may not be necessary pending outcome of PIRT review. Design could proceed to fuel assembly testing.
Procure industry manufactured fuel pellets and cladded fuel elements	CTE1-2.2	Q2/Y2	Industry already operates facilities where fuel pellets and cladding may be able to be fabricated and assembled to the desired size, shape, and quality. Some of the vendors may not be presently licensed to handle HALEU fuel in their lines. This step will assess manufacturing readiness of industry produced fuel which will be used to select or establish a pilot scale production line capable of large-scale fuel pellet manufacture needed for the NEP reactor. Decision point: If at least one and preferably two vendors cannot fabricate the fuel to the size and density requirements, NASA may have to consider funding the industry to establish such a capability (use of national laboratories for the first few flights is also possible). Use of refractory metal claddings or specialty ceramic or composite claddings may require additional time for industry to develop at the appropriate scale/quality.
Assess readiness of industry manufactured fuel pellets & cladded FEs	CTE1-2.3	Q4/Y2	Reconvene PIRT panel to assess the quality and readiness of industry supplied fuel and cladding materials. This step is a possible down-select point for selection of industry article candidate(s) to test.
2500-hour FE nonnuclear environment TRR	CTE1-2.4	Q4/Y2	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.

Table 3.6: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Assemble industry-supplied fuel element	CTE1-2.5	Q4/Y2	Using PIRT and NAR TRR panel recommendations, fabricate, clad, and seal pellets into a robust representative fuel assembly in preparation for 2,500-hour non-nuclear environments and irradiation testing.
Perform non-nuclear environments testing	CTE1-2.6	Q2/Y3	Perform non-nuclear environments testing under laboratory non-nuclear environments for up to 2500 hours.
FE non-nuclear environment post-test evaluation	CTE1-2.7	Q3/Y3	Perform initial post-test evaluation to confirm integrity of fuel and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to irradiation testing.
2500-hour non-nuclear environment TCR & MVR	CTE1-2.8	Q3/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
Burnup and irradiation TRR	CTE1-2.9	Q4/Y2	Perform a peer review of the burnup and irradiation test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Perform burnup and irradiation testing	CTE1-2.10	Q3/Y3	Complete irradiation testing (in-reactor) of a representative fuel element at anticipated operating conditions (prototypic element geometry, temperature, power density, and working fluid or heat transfer interface).
Post-irradiation evaluation	CTE1-2.11	Q4/Y3	Perform initial post-test evaluation to confirm integrity of fuel and cladding is acceptable for proceeding to RXS BrB testing. More detailed post-test evaluation can be performed in parallel to RXS BrB technology advancement tasks.

Table 3.6: Fuel and Related Fuel Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
2500-hour burnup and irradiation testing TCR & MVR	CTE1-2.12	Q4/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
TRL/AD^2 Advancement NAR	CTE1-2.13	Q4/Y3	Peer-evaluation (PIRT Panel and other system experts) to evaluate whether fuel element system testing and modeling efforts have met all goals specified for advancement to TRL 5. Down-selection of alternative fuel component designs may be completed at this step.

3.4.2 Moderator

The primary function of the moderator in the NEP RXS subsystem is to minimize fuel use and reduce the overall size of the reactor subsystem. To enable criticality over reactor lifetime, the moderator must retain its original composition and exhibit acceptable dimensional and structural integrity over a long operating period. BeO and $\mathrm{YH_x}$ are the primary candidates for NEP moderators. Remaining primary development challenges identified for NEP moderators include net-shape moderator fabrication, high temperature, long duration hydrogen retention for $\mathrm{YH_x}$, and high temperature, long duration irradiation stability for BeO (ref. [86]). Higher operating temperatures and longer lifetime hydrogen retention capabilities may be bolstered with moderator coatings which act as hydrogen retention barriers.

Table 3.7: Moderator Major Technology Milestones to TRL 4.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Design and fabricate netshaped moderator geometry using laboratory feed stock	CTE1-3.1	Q4/Y1	Demonstrate ability to produce required shapes with spatially uniform hydrogen loadings; and free of defects, deformities, and localized stress points (Leverages investments by the FSP and NTP projects). Gather material properties of as fabricated materials to close any material property database gaps. Decision point: If required geometries could not be fabricated redesign core with simpler geometries.
1000-hour ME TRR	CTE1-3.2	Q4/Y1	Perform a peer review of the 1000-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Clad, seal and insulate into a moderator assembly and perform non-nuclear environments testing	CTE1-3.3	Q2/Y2	Demonstrate representative fabrication processes necessary to manufacture the moderator element assembly, including all processes to produce the net-shape moderator, cladding, and insulation as well as assembly and bonding techniques. The moderator assembly will be used in non-nuclear environmental testing to demonstrate ability to operate at anticipated operating (temperature, pressure) conditions employing accelerated thermal-aging techniques (∼1000 hours). Samples will be subjected to mechanical and vibrational loads (including those reflective of launch environment) before thermal testing.
ME non-nuclear environment post-test evaluation	CTE1-3.4	Q2/Y2	Perform initial post-test evaluation to confirm integrity of moderator and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to irradiation testing.

Table 3.7: Moderator Major Technology Milestones to TRL 4.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
1000-hour ME nonnuclear environment TCR & MVR	CTE1-3.5	Q1/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met and that proceeding with irradiation testing is appropriate. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues. Decision point: Redesign moderator element and repeat tasks above if size and quality of as fabricated moderators are not satisfactory or as fabricated performance is not satisfactory, Alternatively, discard metal hydride option. Design down-selects to Be compounds if both issues cannot be resolved with design iteration.
2500-hour Fuel/Mod Preliminary Irradiation Campaign TRR	CTE1-3.6	Q4/Y1	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Preliminary Irradiation campaign	CTE1-3.7	Q2/Y2	This step is intended to subject moderator test coupons with representative compositions and microstructures to a relevant range of irradiation conditions (flux, temperature, and total dpa). Irradiation testing is expected to confirm model and literature trends on material response to irradiation including any swelling, embrittlement, or activation products. If unacceptable material performance under irradiation is noted, redesign or down-selection may be required. Decision point: Redesign moderator element and repeat steps above. Alternatively discard metal hydride option Design down-selects to Be compounds if issues cannot be resolved with design iteration.

Table 3.7: Moderator Major Technology Milestones to TRL 4.

Major Technology Milestones to TRL 4	#	**Timeframe (End Date)**	**Significance**
ME Preliminary Irradiation Testing post-test evaluation	CTE1-3.8	Q3/Y2	Perform initial post-test evaluation to confirm integrity of moderator and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to TRL 5 technology advancement tasks.
2500-hour ME Preliminary Irradiation TCR & MVR	CTE1-3.9	Q3/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues. Decision point: Assess need for any modifications such as increased gap side and/or cladding thickness. May necessitate modifications to the design (e.g., lower power density or lower operating temperature). Gross failure will require pursuit of alternative moderator forms, such as beryllium compounds which may result in higher system α or may require additional fabrication technology development.
TRL/AD^2 Advancement NAR	CTE1-3.10	Q3/Y2	Peer-evaluation to evaluate whether moderator material system and related modeling efforts have met all goals specified for advancement to TRL 4 and AD^2 3.

Table 3.8: Moderator and Related Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Procure and test industry manufactured moderator assemblies	CTE1-4.1	Q4/Y2	SME review of the moderator element designs prior to initiation of fabrication by industry - PM approval for fabrication to proceed. This step will assess manufacturing readiness of industry produced moderators. Net shape moderator element demonstration will require MEs to be fabricated and assembled to the desired size, shape and quality with all relevant claddings or coatings, and insulator materials. This activity may be used to select or establish a pilot scale production line capable of largescale ME manufacture for the NEP reactor.
2500-hour ME non-nuclear environment TRR	CTE1-4.2	Q3/Y2	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Assess and evaluate the readiness of industry manufactured moderator assemblies	CTE1-4.3	Q4/Y2	Reconvene an SME panel to assess the quality and readiness of industry supplied moderator and cladding materials. This step is a possible downselect point for selecting an industry test article candidate(s) to test.
Assemble industry-supplied moderator element	CTE1-4.4	Q4/Y2	Using SME and NAR TRR panel recommendations, fabricate, clad, and seal moderators into a robust representative assembly in preparation for 2,500-hour nonnuclear environments and irradiation testing.
Perform ME non-nuclear environments testing	CTE1-4.5	Q2/Y3	Demonstrate ability to operate at anticipated temperature and pressure conditions (∼2,500 hours). Samples will be subjected to mechanical and vibrational loads before thermal testing.
ME non-nuclear environment post-test evaluation	CTE1-4.6	Q3/Y3	Perform initial post-test evaluation to confirm integrity of moderator and cladding is acceptable for proceeding to irradiation testing. More detailed post-test evaluation can be performed in parallel to irradiation testing.

Table 3.8: Moderator and Related Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
2500-hour ME non-nuclear environment TCR & MVR	CTE1-4.7	Q3/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no issues that will prevent further advancement. Decision point: Redesign moderator element and repeat tasks above. Alternatively, discontinue metal hydride option and down-select to beryllium compounds.
Burnup and irradiation TRR	CTE1-4.8	Q4/Y3	Perform a peer review of the burnup and irradiation test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
High fidelity ME burnup and irradiation test	CTE1-4.9	Q3/Y3	Complete higher fidelity irradiation testing (in-reactor) of a representative moderator assembly at anticipated operating conditions (prototypic element geometry, temperature, power density, and working fluid or heat transfer interface) and lifetime. This step may be performed in coordination with fuel element development tasks.
Post-irradiation evaluation	CTE1-4.10	Q4/Y3	Perform initial post-test evaluation to confirm integrity of moderator and cladding is acceptable for proceeding to RXS BrB testing. More detailed post-test evaluation can be performed in parallel to RXS BrB technology advancement tasks.

Table 3.8: Moderator and Related Cladding, Coating Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
2500-hour high fidelity ME burnup and irradiation TCR & MVR	CTE1-4.11	Q4/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no issues that will prevent further advancement.
TRL/AD^2 Advancement NAR	CTE1-4.12	Q4/Y3	Peer-evaluation to evaluate whether moderator element system testing and modeling efforts have met all goals specified for advancement to TRL 5.

3.4.3 Cladding and Coatings

For all reactor technology options, cladding or coating technologies may be required to prevent undesirable fuel or moderator interactions with the working fluid or other reactor structural interfaces (such as HPs and the reactor structural block). In the case of fuel cladding technologies, the cladding can also provide a barrier to fission product release or fuel migration over the lifetime of the core (note: uncontained fission gas release is, in general, not a major safety concern for space application, but it is vital to prevent release for a ground demonstration and minimizing or eliminating release may help limit or eliminate potential chemical interactions between various constituents of the core). For hydride moderators, claddings or barrier coatings may be desired to prevent loss of hydrogen at high temperatures. Fuel- and moderator-cladding technology advancement tasks are already identified in the previous subsections, however additional considerations for low TRL cladding development activities focus on demonstrating the feasibility of radiation tolerant coating/cladding systems that acts as barrier against hydrogen and fission product release. Associated milestones are:

Coatings: demonstrate fabrication of hydrogen and fission product barrier coatings at scale and complexity of relevance (e.g., coating uniformity, delamination resistance, microcrack-free microstructure). Coatings are not required where claddings show acceptable resistance to hydrogen or fission product permeability. For HP materials, show acceptable chemical compatibility enabled by the introduction of protective coatings. Demonstrate coating integrity under all operating conditions including large thermal gradients during nominal operation or other thermal stresses imposed due to off-nominal conditions.

Cladding Tubes: fabricate clad of sufficient geometric sizes and tolerances to meet NEP reactor specifications including aspect ratio, wall thickness, strength, and thermal stability that enables a reactor with target specific mass.

Compatibility: fundamental material compatibility studies with fuel, structures, HPs, etc., under representative irradiation, fluid, and thermal conditions.

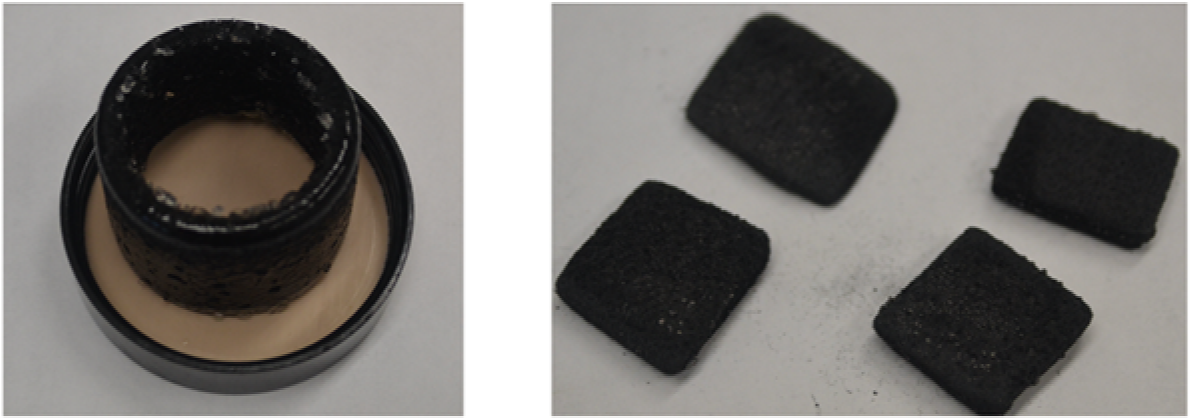
Developed fuel and moderator cladding or coatings will be used in net shape component tests (Tables 3.7-3.8) and in the assembly demonstration (BrB testing).

3.4.4 Insulator

Insulator components are used in the NEP RXS to reduce the temperatures of non-fuel components (such as moderator, reflector, or reactor vessel) during steady state operation (Figure 3.9). There exist MLI materials which do not require fabrication technology development but do require demonstration to validate insulator performance and structural integrity under operating conditions. Other insulator materials for space reactor applications are under development by other NASA programs. To reduce risk prior to integrated fuel assembly or RXS BrB testing, NEP insulator demonstration will be pursued with MLI materials. New insulation technologies will be incorporated if fabrication at the appropriate geometry/scale is demonstrated through other programs and as-fabricated materials are demonstrated capable of meeting NEP thermal property requirements. Recommended development tasks are:

- Perform thermal tests to demonstrate performance of the candidate insulator under design temperatures and thermal gradients.
- Investigate high temperature compatibility of the insulator with relevant components using coupon testing in a high temperature furnace to down-select insulator material options.
- Demonstrate the manufacture of net-shape insulator components and confirm "as fabricated" properties are capable of meeting thermal and mechanical property requirements.
- Perform neutron irradiation studies to demonstrate radiation tolerance under expected nuclear conditions (i.e., representative neutron fluxes and total lifetime or displacements per atom (dpa)) and temperatures of the NEP reactor.
- Perform mechanical integrity tests to demonstrate structural stability under launch and shock environments.

In-core insulator components will be required for successful fuel assembly demonstration (BrB testing).



Carbon preform infiltrated with ZrO_2 sol gel (pre-formed annular jacket on inverted jar lid).

Porous ZrC from C felt preform.

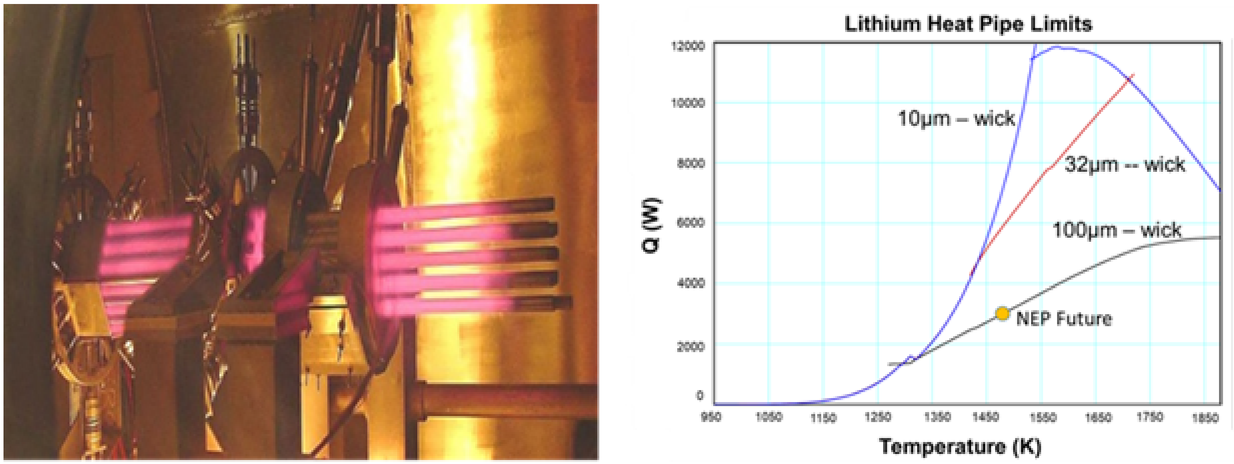
Figure 3.9: Example zirconium-based high-temperature insulator prototypes. Such insulators are being developed as part of SNP project at LANL and ORNL.

3.4.5 RXS Heat Transfer Technologies

Heat transfer technology development needs vary for each of the reactor options and are essential RXS development efforts to ensure the NEP reactor is capable of satisfying KPPs related to the CTE-1 to CTE-2 interface requirements (PCIT, total thermal power). Required heat transfer technology development activities for the direct gas-cooled reactor option are included in the CTE-2 PCS technology advancement plan since this reactor option corresponds to a single loop CTE-1 and CTE-2 subsystem. This section covers technology advancement tasks required for liquid metal HP development.

Liquid Metal Heat Pipe Reactor Heat Transfer Technologies (HPR option only)

Liquid metal HPRs have the capability for high performance, high reliability, fault tolerant reactor designs. Primary working fluid candidates under consideration for current NEP designs include sodium (Na) and lithium (Li), which are projected to be capable of enabling reactor exit interface temperatures of 1200 and 1400 K, respectively. Both Na and Li HPs have been fabricated and tested in nuclear and high-temperature thermal environments (see Figure 3.10). However, Na HPs are assessed to be a higher TRL compared to Li HPs. At the NEP relevant core temperature of roughly 1500 K, a state-of-the-art Li HP can transfer nearly 80 kW_{th} of heat through a 2-inch diameter (implying that 100 optimized HPs of this size and temperature can effectively transfer at least 6 MW_{th} from the core to the heat exchanger). HPs with such capacity can be industrially fabricated with minimal investment. However, the challenge is to find optimal and reliable approaches for bonding or integration of the HPs into the reactor core structures, In addition, the HP assemblies must mate to the PCS through integration with the RXS-PCS heat exchanger. The inherent physics of HP operation and the designs of candidate heat exchangers and condensers remove the necessity of including in the design a gas separator and a subassembly to handle freeze-thaw cycles.



SAFE-100 1.5-cm Na Heat Pipe Testing at MSFC.

Operational envelope for a Molybdenum walled 7-Li heat pipe.

Figure 3.10: Example of liquid metal HPs tested as part of previous space nuclear programs and identified limits for Li HPs.

Proposed development activities (Table 3.9 and Table 3.10, Figure 3.13 and Figure 3.14) for liquid metal HP heat transfer technologies for NEP include low TRL demonstration of candidate HP components to down-select materials and working fluids: stainless steel HP structures with heat transfer enhancements (Na-working fluid at 1200 K or Li-working fluid at 1400 K) and advanced Mo HP structures (Mo-walled, Mo-wicked HPs with Li-working fluid at 1400 K). Following down-selection, advancement activities will focus on manufacture and demonstration of prototypic scale HPs with a representative core and heat exchanger interface to verify thermal performance, such as the ability to satisfy PCIT conditions and thermal power throughout per HP (25–30 $\mathrm{kW_{th}}$). Final development activities will seek to demonstrate the HP operation in a nuclear environment and NAR of test data to approve of the readiness of new HP technologies. The BrB will demonstrate ability of HP technologies to achieve specific weight requirements while performing reliably.

Table 3.9: Liquid Metal HP Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Design and fabricate finned condenser HP	CTE1-5.1	Q3/Y1	Design and fabricate steel-sodium HPs with special features, such as fins, to enhance heat transfer area in the condenser region to minimize length of the heat exchanger necessary to remove heat at highest rated capacity Decision point: Design features perform to requirements. If necessary, redesign HP
Design and fabricate advanced wick (Mo)	CTE1-5.2	Q3/Y1	Demonstrate manufacturing line capability to fabricate a Mo wick with 10-25 micrometer pore radius. Decision point: If manufacture cannot be demonstrated, examine if stainless steel wicks can perform reliably at 1400 K with Li or baseline a 1200 K-Na HP.
1000-hour HP TRR	CTE1-5.3	Q3/Y1	Perform a peer review of the 1000-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures for both HP candidates.
Finned condenser HP demonstration	CTE1-5.4	Q1/Y2	Demonstrate performance of steel-sodium HP under relevant heat flux and temperature conditions. Verify operational behavior of the HP over extended durations.
Advanced wick demonstration	CTE1-5.5	Q1/Y2	Demonstrate performance of molybdenum-lithium HP under relevant heat flux and temperature conditions. Verify operational behavior of the HP over extended durations.
1000-hour HP demonstration TCR & MVR	CTE1-5.6	Q1/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met and that proceeding with irradiation testing is appropriate. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.

Table 3.9: Liquid Metal HP Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
TRL/AD^2 Advancement NAR	CTE1-5.7	Q1/Y2	Peer-evaluation to demonstrate that reactor HP and related modeling efforts have met all goals specified for advancement to TRL 4 and AD^2 3. Down-select HP design for NEP reactor. Identify updated reference operating conditions for the reference HP and reactor subsystem components.

Table 3.10: Liquid Metal HP Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Design and fabricate HP heat exchanger assembly for non-nuclear testing	CTE1-6.1	Q3/Y2	Fabricate and assemble a representative HP-heat exchanger assembly at a representative scale. Demonstrate relevant assembly and joining techniques.
2500-hour high temperature/high throughput TRR	CTE1-6.2	Q3/Y2	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures for both the HP and heat exchanger components.
High temperature, high throughput HP demonstration	CTE1-6.3	Q4/Y2	Demonstrate high through-put (up to 25-30 kW_{th}) HPs with special features to enhance heat transfer to He-Xe to demonstrate feasibility of achieving required thermal performance and α using non-nuclear testing.
2500-hour high temperature/high throughput TCR & MVR	CTE1-6.4	Q4/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met and whether proceeding with irradiation testing is appropriate. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models. Update FMEA analyses to include the results of testing and confirm there are no issues that will prevent further advancement.

Table 3.10: Liquid Metal HP Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Design and fabricate HP for irradiation testing	CTE1-6.5	Q4/Y2	Fabricate and assemble a representative HP at a representative scale for irradiation testing.
2500-hour reactor environment TRR	CTE1-6.6	Q4/Y2	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Long duration burnup and irradiation test	CTE1-6.7	Q1/Y3	Demonstrate HP radiation tolerance through irradiation and long-term (2,500 hours) testing at anticipated operating conditions in a reactor environment. HPs may be integrated into the fuel assembly long burn up and irradiation test.
Long duration burnup and irradiation TCR & MVR	CTE1-6.8	Q1/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no issues that will prevent further advancement.
TRL/AD^2 Advancement NAR	CTE1-6.9	Q1/Y3	Peer-evaluation to demonstrate that HP testing and modeling efforts have met all goals specified for advancement to TRL 5. Perform a down-select of heat transfer technologies and select operating conditions for the NEP Reactor. Decision point: If HPs are not capable of meeting required performance, exclude further development into high performance HP-based designs if Mo-Li HP (limit reactor operation to 1200 K) or use alternative reactor heat transfer technology.

3.4.6 Pressure Vessel (HTGR option only)

Pressure vessels serve multiple purposes: (1) as the primary containment for the reactor core and physical interface to transfer the working fluid from the reactor to the PCS components and/or (2) as the containment for working fluid in the heat exchanger. Emphasis of this technology maturation sub-task is demonstration of a low specific mass containment system that can support a HTGR design.

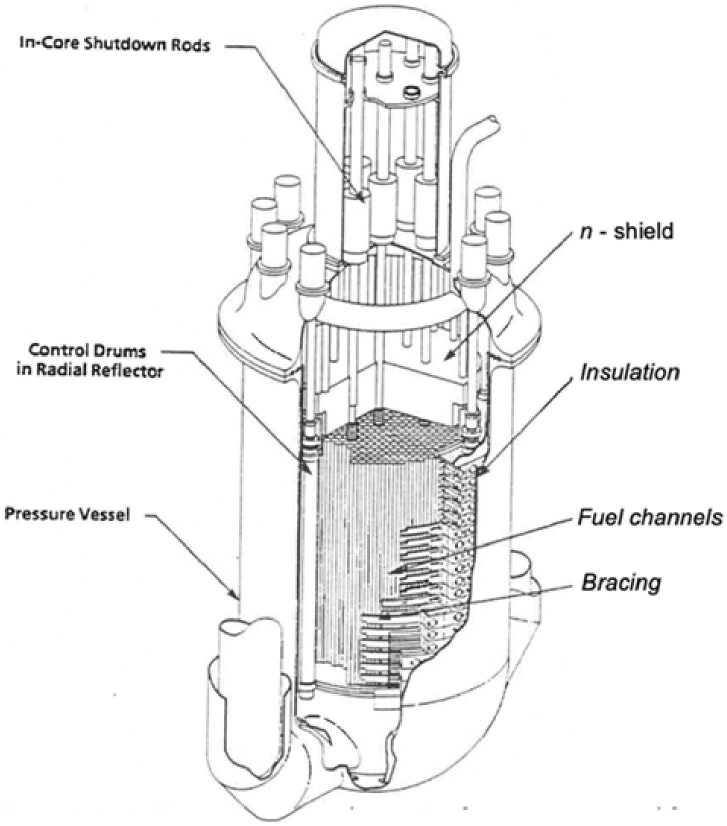


Figure 3.11: Representative schematic of a pressure vessel for a HTGR concept.

The pressure vessel design will vary based on the reference reactor options, however general design conditions include the 1–3 MPa pressure capability and operating temperatures up to 1500 K temperatures. Figure 3.11 is a schematic representation of a pressure vessel containment system for a direct gas cooled reactor operating at 1500 K. This design includes multiple radiation shields and thermal insulation layers to ensure the pressure vessel retains its ductility and remains creep free. Furthermore, "cold" inlet gas is circulated around the reactor core to maintain the vessel and piping structures well below 1000 K. The design also consists of numerous penetrations for control system and instrumentation integration. While details of a particular vendor's design might differ from Figure 3.11, the technology gaps remain the same. Pressure vessel designs aim to minimize mass while maintaining compliance with American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) code or equivalent standards. Pressure vessels must be capable of extended operations at high temperatures while resisting creep (elastic-plastic deformation) or property degradation due to interaction with impurities present in the working fluid. While ASME BPV code limits are well established for LWR reactors (elastic deformation only) and work has been performed for establishing terrestrial HTGR BPV code limits (elastic-plastic deformation), design challenges are expected in adapting existing codes for higher operating temperatures and other conditions and operational variations unique to NEP applications. For example, the design must ensure that for all operating modes, including transients, brittle failure can be avoided for alloys that exhibit a ductile to brittle transition temperature (DBTT). Milestones listed in Table 3.11 and Table 3.12 (Figure 3.16 and Figure 3.17) allow for technology gaps to be addressed in the development plan. The activities included in this section only apply to the HTGR RXS option and these activities would not be pursued in the case of a down-selection to the HPR option.

Table 3.11: RXS Pressure Vessel Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Design Assessment	CTE1-7.1	Q2/Y1	Design a pressure vessel with necessary features (e.g., welds and joining) that can enable a direct He-Xe cooled reactor with target α. Alternate assessments should examine performance at the target temperature of 1400 K and nominal and off-nominal operating conditions. Designs will be compliant with the American Society of Mechanical Engineers Boiler and Pressure Vessel codes or equivalent standards.
Pressure Vessel Fabrication Demonstration	CTE1-7.2	Q3/Y1	Demonstrate representative fabrication and assembly processes for the pressure vessel design. The as-fabricated vessel will be used in non-nuclear testing. Verify acceptable hermeticity of the fully assembled vessel and resistance to working fluid leakage.
2500-hour RXS pressure vessel advancement TRR	CTE1-7.3	Q4/Y1	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.

Table 3.11: RXS Pressure Vessel Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Vessel non-nuclear testing	CTE1-7.4	Q2/Y2	Test a pressure vessel assembly at the anticipated operating, off-nominal and accident conditions for 2,500 hours. The test plan should capture the number of transients expected during operation, thermal cycling is extremely important for vessels constructed of refractory alloys. Verify under all conditions that pressure vessel performance is acceptable and avoids brittle failure modes that may occur below the DBTT. Gather material properties of as fabricated materials to close any material property database gaps. Perform chemical compatibility testing (representative temperature, pressure, gas velocities) with representative material coupons (including any welds) in He-Xe gas mixtures with representative impurity contents if data gaps exist.
Vessel non-nuclear testing TCR & MVR	CTE1-7.5	Q2/Y2	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met and that proceeding with irradiation testing is appropriate. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
TRL/AD^2 Advancement NAR	CTE1-7.6	Q2/Y2	Peer-evaluation to evaluate whether pressure vessel testing and modeling efforts have met all goals specified for advancement to TRL 4 and AD^2 3.

Table 3.12: RXS Pressure Vessel Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Industry manufacturing readiness assessment	CTE1-8.1	Q2/Y3	Industry design and fabrication of a FS pressure vessel including NDE and DE. This step will assess manufacturing readiness of industry produced vessels. Prototypic scale vessel demonstration will require vessels to be fabricated and assembled to the desired size, shape and quality with all relevant interfaces or piping components.
2500-hour RXS pressure vessel performance TRR	CTE1-8.2	Q2/Y3	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Vessel component level performance verification though non-nuclear testing	CTE1-8.3	Q3/Y3	Fabricate and test a full-scale assembly at the anticipated operating, off-nominal, and accident conditions for 2,500 hours. Thermal cycling is extremely important for vessels constructed of refractory alloys. Include laboratory testing conditions to demonstrate resilience of the system against potential meteor strikes and other off-nominal operating conditions.
Non-nuclear vessel component level performance verification TCR & MVR	CTE1-8.4	Q3/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
TRL/AD^2 Advancement NAR	CTE1-8.5	Q3/Y3	Peer-evaluation to evaluate whether pressure vessel testing and modeling efforts have met all goals specified for advancement to TRL 5. Use test data and validated structural mechanics tools to project performance at target operating conditions and use available performance data to down-select RXS heat transfer technology and operating conditions if applicable

3.4.7 Reflector Assembly

BeO is the primary material candidate for the reflector and is a well understood material. Several US companies are capable of manufacturing BeO at both the scale and purity levels required for NEP. One activity proposed for this component is demonstrate manufacturing readiness of BeO reflector assembly through industry engagement. The manufactured assemblies could be used for mechanisms testing in relevant non-nuclear environments (including nominal operation in a vacuum or operational atmosphere while at representative temperatures). Assemblies could also be subjected to non-nuclear testing for conditions representative of startup and could even be included as part of the BrB unit testing.

3.4.8 RXS Instrumentation and Control System

The primary goals of the development of the NEP RXS instrumentation and control (I&C) system is to develop the hardware and sensors required to enable reliable, predictable, controllable operation of the reactor. Primary I&C development challenges for the reactor include development and manufacture of reactor control system components and actuators, as well as the maturation of monitoring instrumentation capable of surviving the combined space and nuclear operating environment for target NEP lifetimes. Development of control system logic and software related to the reactor is also considered in this task. I&C software development is important to ensure desirable response and control of the reactor for all nominal conditions as well as fault detection and response scenarios for off-nominal operations. The I&C development tasks are summarized in Table 3.13 and 3.14 (Figure 3.7 and 3.8).

Table 3.13: RXS I&C Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Design assessment including FMEA	CTE1-9.1	Q4/Y1	Design a fault-tolerant control system making use of space qualified and radiation-tolerant electronics and communication components, relays, actuators, motors, and state-of-the-art sensors (fission, temperature, pressure, displacement, and other system variables). Identify all relevant NEP reactor modes of operation and functional logic for the control system. Decision point: Identify the extent to which existing technologies are capable of operation to enable NEP performance requirements, including nuclear and space operational environments.

Table 3.13: RXS I&C Technology Advancement Tasks (TRL 4).

Major Technology Milestones to TRL 4	#	**Timeframe (End Date)**	**Significance**
I&C Testbed design and assembly	CTE1-9.2	Q3/Y2	Commence design activities for a non-nuclear I&C test bed. Develop a control algorithm that could allow for testing of instrumentation functionality relevant to NEP reactor operating modes. Procure or produce instrumentation for operation in the I&C test bed.
I&C Testbed TRR	CTE1-9.3	Q3/Y2	Perform a peer review of the I&C test bed test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
I&C Testbed Operational Testing	CTE1-9.4	Q4/Y2	Demonstrate fault-tolerant performance through a hybrid architecture consisting of I&C hardware, prototype reactor components, and software that simulates reactor and PCS system response. Decision point: Repeat steps above. Alternately identify needs for new technologies and develop a TMP for the identified component.
I&C Testbed Operations TCR & MVR	CTE1-9.5	Q4/Y2	Using available test data, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed test bed operations to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Perform more detailed test bed operations ahead of the TRL/AD^2 Advancement NAR. Update FMEA analyses to include the results of testing and confirm there are no outstanding issues to prevent further advancement.
TRL/AD^2 Advancement NAR	CTE1-9.6	Q4/Y2	Peer-evaluation to evaluate whether I&C testing and modeling efforts have met all goals specified for advancement to TRL 4 and AD^2 3. Down-select instrumentation for further development and establish separate effects testing needs to evaluate instrumentation under relevant environments.

Table 3.14: RXS I&C Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
I&C Separate Effects TRR	CTE1-10.1	Q4/Y2	Perform a peer review of the separate effects irradiation test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Initiate radiation hardening testing program in university reactors	CTE1-10.2	Q4/Y2	Demonstrate component's radiation tolerance under representative irradiation environments (neutron and gamma flux, temperatures, and fluences). Decision point: Shielding and placement with respect to the reactor core conform to weight and operability requirements. Unacceptable performance may require new instrumentation selection or redesign, which will require steps 1 and 2 in Table 3.13 to be repeated.
Separate effects post-test evaluation	CTE1-10.3	Q3/Y3	Perform initial post-test evaluation to confirm integrity of instrumentation is acceptable for proceeding to RXS BrB testing. More detailed post-test evaluation can be performed in parallel to RXS BrB technology advancement tasks.
Separate Effects Test Complete Review TCR & MVR	CTE1-10.4	Q4/Y3	Using available test data, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no issues preventing further advancement.
TRL/AD^2 Advancement NAR	CTE1-10.5	Q4/Y3	Peer-evaluation to demonstrate that I&C component system testing and modeling efforts have met all goals specified for advancement to TRL 5.

3.4.9 Reactor Assembly Engineering Scale Brassboard

High-fidelity near-scale non-nuclear test beds and subscale nuclear testing can be used to quickly reduce overall design uncertainty and to minimize the scope and duration of ground nuclear demonstration. The term "near-scale" refers to a representative prototype of the core that is geometrically smaller, but accurately captures all the relevant physical phenomena.

Robust approaches exist for using uncertainty quantification methods to design representative geometries. The US Nuclear Regulatory Commission (NRC) has traditionally relied on Code Scalability, Applicability and Uncertainty (CSAU) approach for integrating separate effects testing into the overall licensing process (ref. [86]). Quantification of Margins and Uncertainties (QMU) is the peer reviewed approach used by the National Nuclear Security Administration (NNSA) laboratories for assessing stockpile safety and performance (refs. [68, 87]). The SNP NEP project plans to adapt CSAU/QMU approaches to buy-down risk in early phase of development. Successful demonstration of the assembly scale engineering demonstration unit allows for the NEP RXS core component technologies to meet TRL 5 maturation goals. Proposed tasks are as follows (milestones included in Table 3.15 and Figures 3.7 and 3.8).

1. Perform scaling analyses to design a representative prototype core assembly. Make use of CSAU methods and peer reviews to confirm that representative assembly together with accompanying modeling and simulation will be sufficient to quantify uncertainty and bound necessary margins. Figure 3.12 illustrates the capability of translating a nuclear fuel assembly into an process to be used for determining the scale and size of the fuel assembly for the engineering demonstration unit (EDU).

2. Design and build a high-fidelity nuclear test bed for demonstrating a BrB (engineering scale) unit. Figure 3.13 is a notional representation of the testing capabilities required for BrB testing.

3. Perform multi-scale, non-nuclear testing starting with assembly level testing and culminating in near-scale representative assembly (non-nuclear BrB). Though a majority of experimental facilities already exist for this step, it is likely that a new facility would be needed for the integrated subsystem testing — which is expected approach about 1 MWth-thermal power demonstration (roughly 1/6 scale). Figure 3.14 illustrates testing configurations and setup for BrB demonstration. The near-scale representative assembly will include all RXS technologies matured through the CTE-1 TMP and reactor heat exchanger.

4. Verify reactor physics through zero/low power critical testing. This step is vitally important for the moderated reactors because both the hydrides and beryllium-compounds possess positive reactivity feedback. For such systems, it is essential that both the magnitude and timing of reactivity feedback is well characterized. Figure 3.15 illustrates important nuclear development testing proposed as part of BrB.

5. Demonstrate prototypic scale fuel assembly performance through combined effects irradiation under nominal and transient nuclear environments to characterize reactor core component performance under representative combined effects conditions at steady state and possible reactivity insertion or operational transients.

Item 5 is not necessary to be completed before reactor down select. It is however necessary to be completed before work commences on a ground test nuclear demonstration.

Table 3.15: RXS Assembly Scale BrB Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Facilities and Scalability Assessment Studies	CTE1-11.1	Q1/Y1	Identify available facilities to support BrB testing and required modifications to enable testing under desired non-nuclear, nuclear (critical), and irradiation BrB test conditions.
Facilities Design Review	CTE1-11.2	Q4/Y1	Perform a facilities design review to assess the readiness of facilities to support BrB testing.
Initial Draft IDD, FMEA, Risk and Hazard Lists	CTE1-11.3	Q4/Y1	SME-developed interface description document (IDD), failure modes and effects analysis (FMEA), and hazards lists drafted.
BrB Design Assessment Initiated	CTE1-11.4	Q2/Y2	Design a representative/protype fuel assembly that accurately scales full-reactor performance. Assembly accurately scales fuel elements, moderator elements, HPs or pumping loop, and all structural features. It also includes all the in-core elements of the I&C. Scaling rationale verified through US NRC Code Scalability Applicability and Uncertainty process that includes high fidelity simulations. PM approves fabrication of the assembly based on peer review by the PIRT panel.
Design and build test bed for thermal testing	CTE1-11.5	Q3/Y3	Demonstrate assembly thermal, mechanical and chemical performance making use of a high-fidelity engineering demonstration test bed (including reactor heat exchanger) to be established at location TBD. Test bed accurately reproduces anticipated thermal, chemical, and mechanical environments. Demonstration will be carried out for 2500 hours. Characterize fluid state points at component inlet/exit positions and use test data to confirm developed system and component models. Verify leakage of working fluid is not present or characterize leakage rate.
Facilities modifications for critical testing	CTE1-11.6	Q3/Y3	Using down-selected reactor component technologies, and target reactor operating conditions determined from component level TRL 4 and AD^2 3 or TRL 5 NARs.
Facilities modifications for irradiation testing	CTE1-11.7	Q3/Y3	Using down-selected reactor component technologies, and target reactor operating conditions determined from component level TRL 4 and AD^2 3 or TRL 5 NARs.

Table 3.15: RXS Assembly Scale BrB Technology Advancement Tasks (TRL 5).

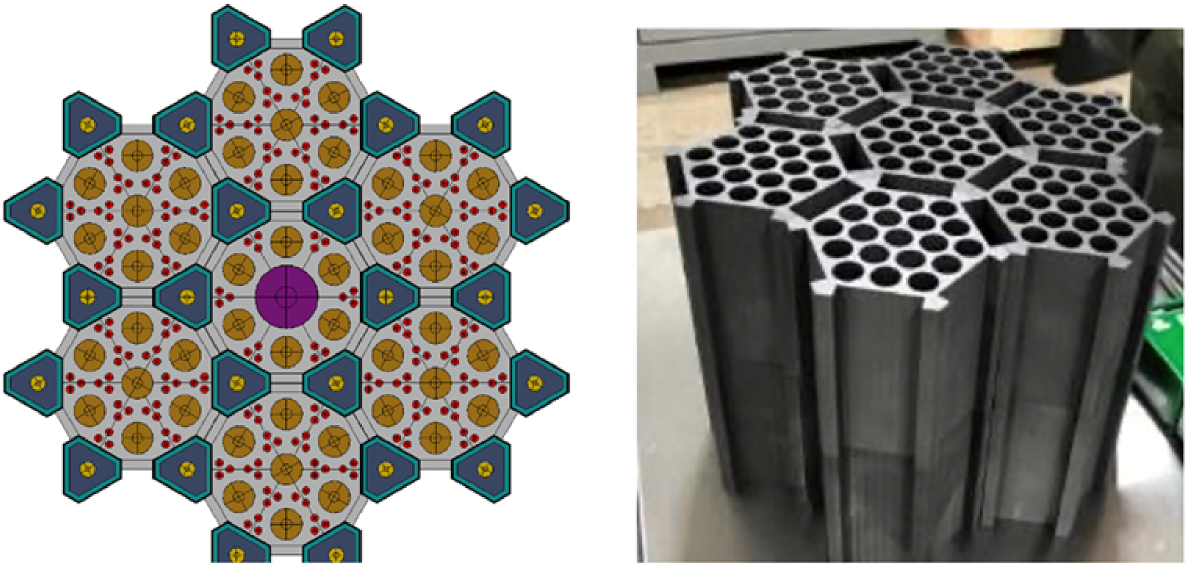
Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
BrB Fuel Assembly Fabricated	CTE1-11.8	Q3/Y3	Demonstrate industry/laboratory fabrication capability through fabrication of the assembly to the required precision and quality followed by thermal, mechanical and vibration testing. Mechanical and vibration tests should also factor in conditions related to launch and shock environments. A scaling analysis will be used to prescribe testing conditions.
2500-hour thermal performance TRR	CTE1-11.9	Q3/Y3	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Verify long-duration thermal performance	CTE1-11.10	Q4/Y3	Test a FS assembly at the anticipated operating, off-nominal, and accident conditions for 2,500 hours, including representative number of thermal cycles.
Thermal Performance BrB TCR & MVR	CTE1-11.11	Q4/Y3	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
2500-hour neutronic performance TRR	CTE1-11.12	Q4/Y3	Perform a peer review of the 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures.
Verify neutronic performance (critical testing)	CTE1-11.13	Q2/Y4	Demonstrate assembly reactivity characteristics through zero-power and low-power criticality testing. Include instrumentation and test operations required nuclear data to confirm reactor physics calculations. Note: the DOE already possesses required facilities for performing this type of tests.

Table 3.15: RXS Assembly Scale BrB Technology Advancement Tasks (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Neutronic Performance BrB TCR & MVR	CTE1-11.14	Q2/Y4	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
Irradiation and reactivity insertion performance TRR	CTE1-11.15	Q2/Y4	Perform a peer review of the test plan including test objectives, test duration, selected facilities, test article design, testing conditions, and testing procedures.
Verify irradiation and reactivity insertion performance	CTE1-11.16	Q3/Y4	Demonstrate burnup survivability through exposure to representative neutron/photon fluxes in a reactor environment. Irradiation performance through full-assembly testing. Reactivity insertion testing at a transient reactor test facility.
Post-test evaluation	CTE1-11.17	Q3/Y4	Perform initial post-test evaluation to confirm integrity of RXS bread board BB including relevant components.
Irradiation and Reactivity Insertion Performance TCR & MVR	CTE1-11.18	Q4/Y4	Using available test data and post-test evaluation, complete a non-advocate test completion review to evaluate whether test objectives have been met. Complete a model validation review to develop a plan to use available test data and perform more detailed post-test inspection to provide an adequate level of validation for existing models and identify required changes necessary on the component, subsystem, and system level scales. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
Assembly performance verification complete	CTE1-11.19	Q4/Y4	Use test data from the testing program to modify and validate state-of-the-art models to project performance at target operating conditions.
TRL/AD^2 Advancement NAR	CTE1-11.20	Q4/Y4	Peer-evaluation to demonstrate that BrB testing and modeling efforts have met all goals specified for advancement to TRL 5.

Table 3.15: RXS Assembly Scale BrB Technology Advancement Tasks (TRL 5).

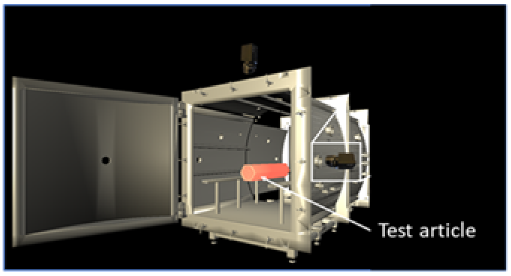
Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Final IDD, FMEA, Risk and Hazard Lists	CTE1-11.21	Q4/Y4	Final TRL 5 IDD revised as necessary for future development. Revisions to FMEA. Risk and hazards lists compete. Documents delivered to SNP.



Example of NEP reactor cross-section. Actual NEP down-select decision is not made. This is shown to demonstrate the process.

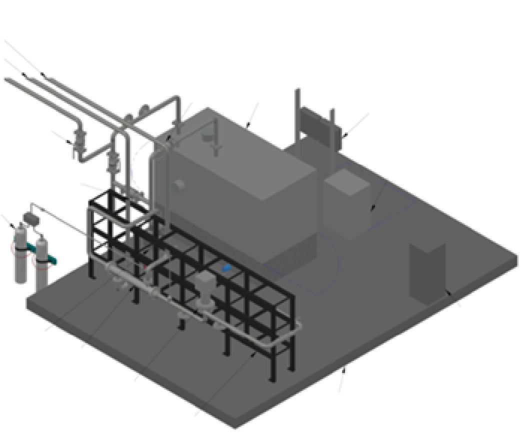
Demonstration of 'brass-board' quality manufacture and assembly of representative core block.

Figure 3.12: Example images of how a reactor core unit cell can be translated into a SS test article. Established scaling considerations, supported by modeling and simulation, will be used to design, fabricate, and assemble a BrB quality fuel assembly.



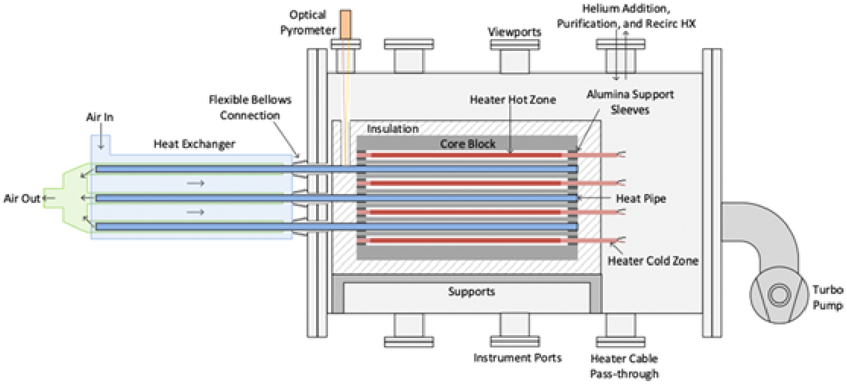
(a) Component qualification through thermal cycling

(b) Full-scale non-nuclear reactor system will be tested in high fidelity test-beds.

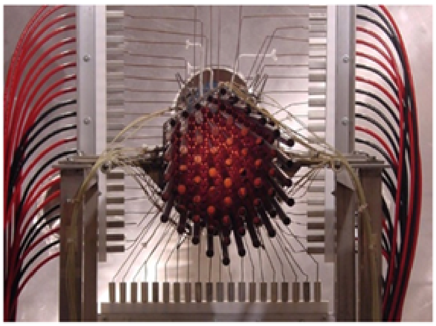


(c) Example versatile test bed for demonstrating technology readiness of NEP Reactor Designs.

Figure 3.13: Multiple views of possible non-nuclear test bed facilities with the potential to support BrB-fidelity RXS testing.



Long-term testing of ‘brass-board’ quality representative core block. Test setup will be equipped with brass-board quality heat-exchanger and instrumentation and sensors. Electrical heating (shaped induction heaters) will substitute for fission heat



Shaped electrical heaters will be used to be accurately representative of axial and radial heat fluxes.

Figure 3.14: Example Testing Options to Perform Long-term (2500 hours) Test to Demonstrate Performance of the BrB. Bottom image, example non-nuclear heater for HP testing and top image, schematic representation of a notional non-nuclear BrB-fidelity Liquid Metal HP reactor simulator.

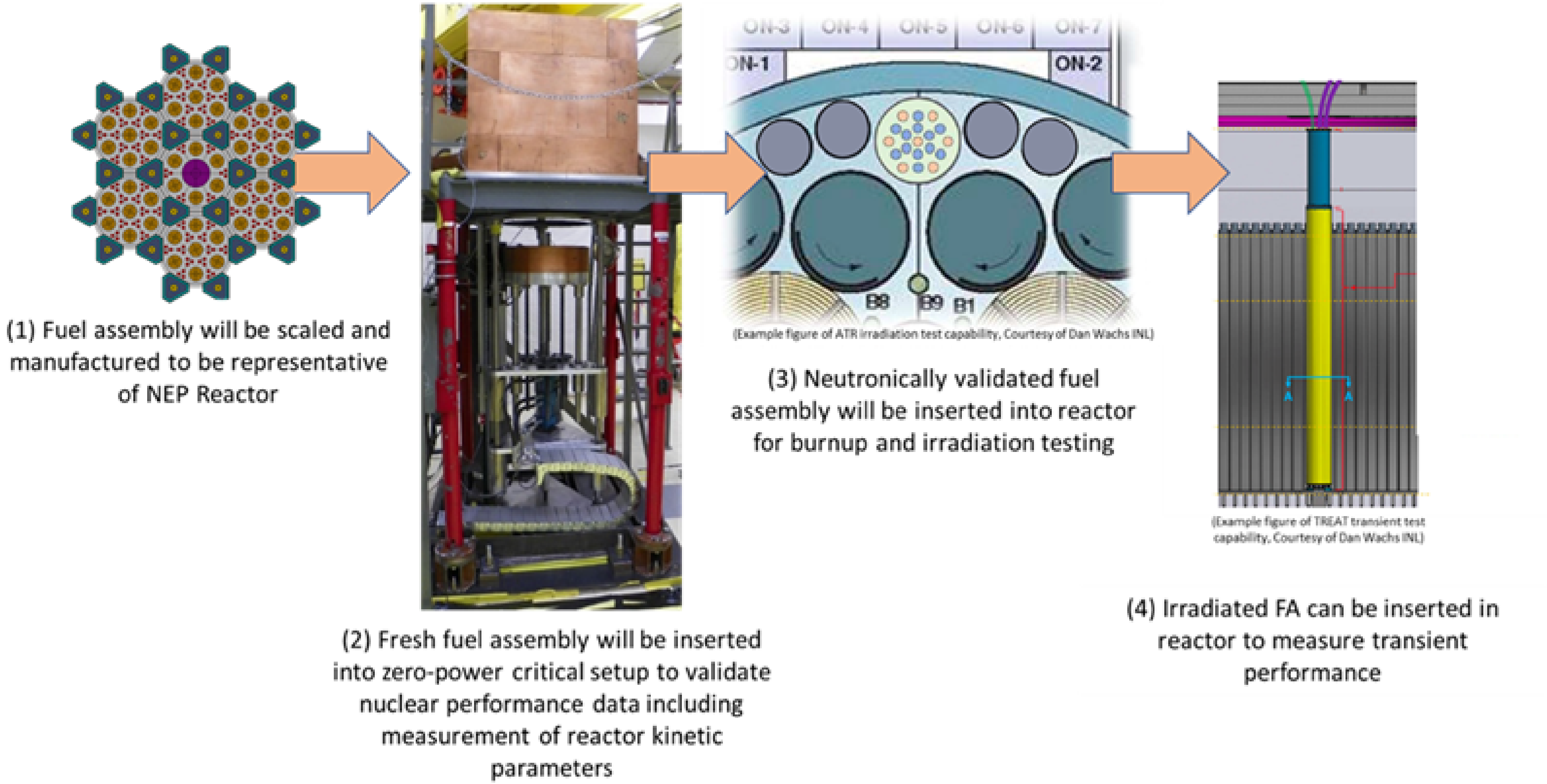


Figure 3.15: Proposed multi-scale nuclear physics experiments for validating NEP RXS fuel assembly (FA) design and demonstration to establish TRL 5.

3.4.10 Modeling and Simulation

No new code development is planned as part of modeling and simulation for the RXS. Modification of existing codes with targeted development to enable analysis of NEP RXS systems will be performed in support of RXS hardware development and planned system/mission modeling. Figure 3.16 illustrates the multi-scale multiphysics approach being proposed for modeling of the NEP reactor system using existing Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools. The focus of RXS M&S activities is to use two different sets of computer codes to perform code-to-code verification and use RXS hardware test data to perform experiment-to-code validation (Table 3.16 and Figure 3.16). The objective of the proposed RXS M&S development plan is to allow for RXS-PCS integrated system simulation.

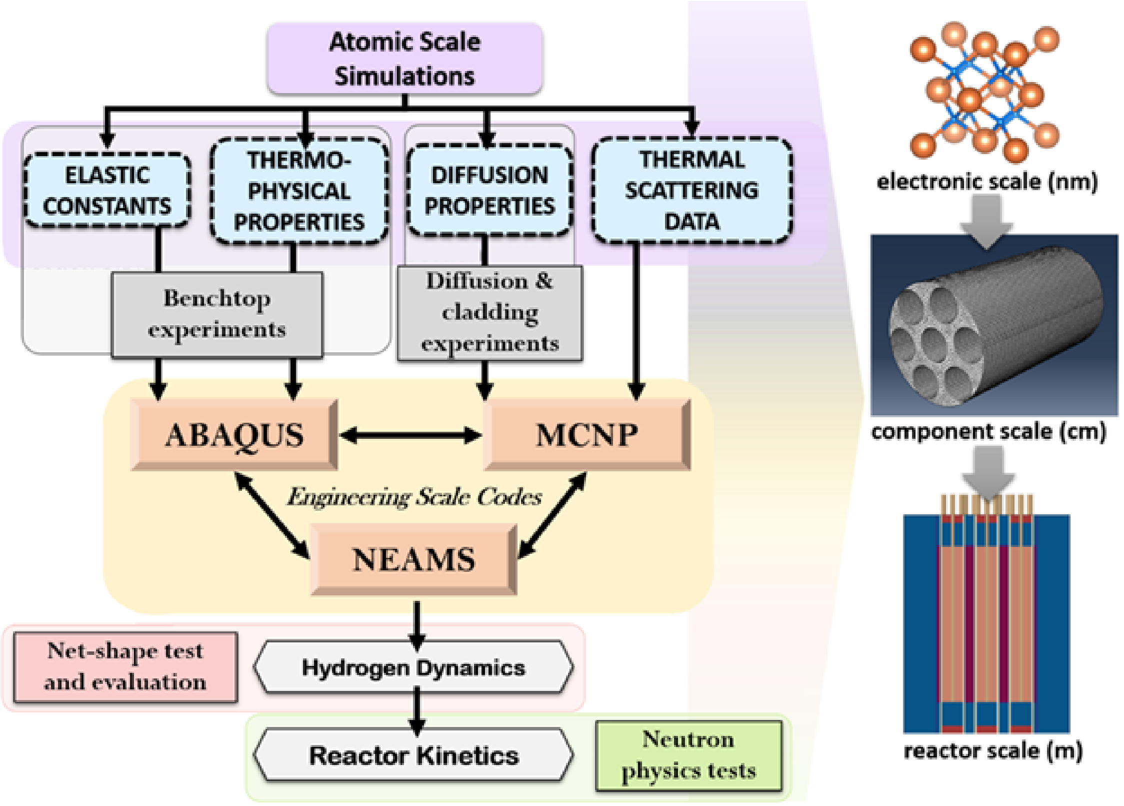


Figure 3.16: Multiscale multiphysics framework for qualifying a moderated HALEU reactor system.

Table 3.16: RXS Modeling and Simulation technology advancement tasks.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Model Workshop	CTE1-12.1	Q1/Y1	Kick off modeling and simulation activities with a model workshop. The workshop should include representatives or SMEs from all relevant disciplines. The workshop should also include representatives from other CTEs to ensure the developed RXS subsystem models are capable of future integration into a robust and integrated system level model.
Gap Assessment	CTE1-12.2	Q4/Y1	US NRC Code Scalability Applicability and Uncertainty process – which includes phenomena, identification, and ranking process – will be used to assess modeling gaps at the component and reactor system level. DOE's NEAMS codes will provide the modeling architecture. Establish a schedule driven stepwise validation of each component and overall reactor system models. Peer-evaluation (MVRs) allows for assessment of test data that can be used for validation in proposed RXS M&S TMP Tasks below.
Initiate RXS component, system, and FMEA model development	CTE1-12.3	Q4/Y1	Component, system, and FMEA models will be needed to support RXS technology maturation activities. Model development for the candidate NEP RXS system design(s) should be initiated early in the project to support design activities and test planning.
TRL 4 and AD^2 3 RXS model update complete	CTE1-12.4	Q4/Y2	Update RXS component models, FMEA models, and reactor subsystem model with TRL 5 test data and MVR results.
Integration of CTE-1 reactor component and system models with CTE- 2 system model	CTE1-12.5	Q4/Y2	Develop a CTE-1 and 2 integrated systems model including instrumentation and controls.
Initiate transient performance modelling	CTE1-12.6	Q4/Y3	Update existing RXS component, system, and integrated systems models to allow for transient analysis. Perform transient analysis to predict BrB system performance for RXS BrB tasks.
TRL 5 RXS model update complete	CTE1-12.7	Q2/Y4	Update RXS component models, FMEA models, and reactor subsystem model with TRL 5 test data and MVR results.

Table 3.16: RXS Modeling and Simulation technology advancement tasks.

Major Technology Milestones to TRL 5	#	**Timeframe (End Date)**	**Significance**
Validate RXS component models	CTE1-12.8	Q2/Y4	Individual models for each subsystem/component are independently validated using test data from previous steps. Uncertainty quantification methods are used to assess modeling uncertainties.
Validate reactor system model	CTE1-12.9	Q2/Y4	Demonstrate a coupled reactor and power conversion system model that adequately predicts system reliability, robustness, and margins with a particular emphasis on reactor controls and fault-tolerance during nominal and off-nominal phases.
Integrate into NEP system model	CTE1-12.10	Q4/Y4	Perform integrated assessment that provides reasonable upper and lower bounds for reactor and PCS α.
TRL/AD^2 Advancement NAR	CTE1-12.11	Q4/Y4	Peer-evaluation to establish that modeling and simulation efforts have met all goals specified for advancement to TRL 5.

3.5 CTE-1 RXS Technology Advancement Risks

This assessment is the start of a formal FMEA, the results of which will be documented as part of the overall RXS technology development effort. Table 3.17 and Figure 3.17 present the ‘Top 5’ technical risks identified at this point by SNP SMEs. All risks will be fully described with risk assessments using NASA’s standard risk scale for consequence and likelihood as taken from Goddard Procedural Requirement (GPR) 7120.4D, Risk Management Reporting.

Table 3.17: 'Top 5' RXS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
RXS-1	Unacceptable reactor and coolant system α	Planned designs employ metallic reactor and/or heat-exchanger vessels to contain power conversion working fluid operating at high temperatures (1200-1400 K) and pressures (1-4 MPa).	T	3	3	9	Reduce vessel mass by reducing operating temperature - Use active vessel cooling methods to reduce vessel wall temperature (improves mechanical properties) which allows for (lower wall thickness). Efficacy was demonstrated during JIMO program and widely used in many industrial applications. Reduce heat exchanger mass - Micro-channel refractory metal heat-exchangers manufactured through additive manufacturing. Reduce reactor mass by minimizing thermal and fluid-structural stresses and required component volumes - Minimize operating pressure and temperature. Reduce vessel mass by developing alternative, low density material systems - Develop high entropy refractory alloys for vessels.

Table 3.17: ‘Top 5’ RXS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

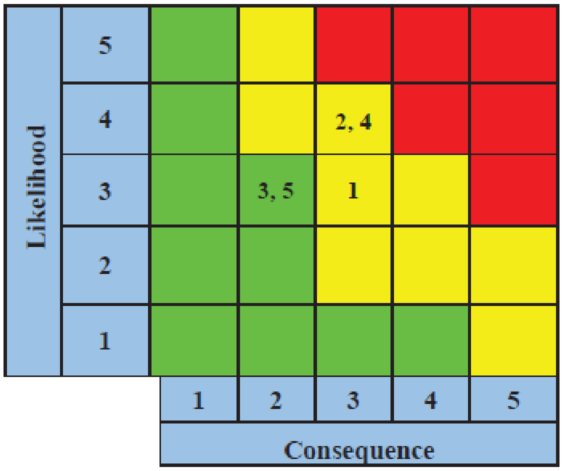
Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
RXS-2	High temperature hydride moderators do not achieve performance goals	Unanticipated materials degradation leading to excess hydrogen loss during operation.	T	4	3	12	Simultaneously pursue reactor designs that rely exclusively on BeO (or Be_2C) moderators. Carry forward Be_2C maturation as risk mitigation strategy. Fully funded schedule reserve for design modifications if BeO/Be_2C fail to achieve maturity.
RXS-3	Clad ceramic fuel pellets do not achieve performance goals	Unanticipated degradation (swelling, loss of conductivity, etc.) of the fuel pellet under anticipated temperature/burn-up conditions.	T	3	2	6	Early and repeated irradiation of UO_2 and UN fuel pins in various reactors, such as MIT-R and ATR. On-ramp particle fuels from the NTP project. Fully funded schedule reserve to revise reactor designs towards lower power density and burnup.

Table 3.17: 'Top 5' RXS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
RXS-4	Unacceptable thermal performance due to heat transfer limitations	Inability to achieve efficient heat transfer to He-Xe due to larger than expected interface contact resistance due to deformation, delamination, cracking, fouling or abnormal flow distributions or inability to handle high thermal loads from multiple simultaneous failures or core assembly deformations under launch loads leads to loss of contact	T	4	3	12	Early transient assessments to reasonably bound off-nominal conditions such as single- and multiple-failures. Provide large margin to accommodate degraded performance. Early assessment through testing and M&S of assembly performance in stepwise fashion at anticipated, acceleration, vibrational and mechanical loads. Stepwise testing of heat-pipes and coolant channel liners (in case of Li or He-Xe cooled system) for accurately estimating range of possible heat transfer coefficients under nominal and off-nominal conditions. Stepwise testing of SS fuel assembly under nominal and off-nominal conditions. Fully funded schedule reserve for redesign with lowered power densities, braces, and other structural reinforcements.

Table 3.17: 'Top 5' RXS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
RXS-5	Unacceptable core neutronic and thermal performance due to neutronic data gaps	Purity of ceramic composites, unknown alloy compositions and hydrides neutron cross-section data base gaps lead to designs with unacceptable neutronic and thermal performance including positive reactivity feedback	T	3	2	6	Early coupled neutronic and thermal simulations combined with uncertainty quantification and variance reduction methods to assess neutronic performance during nominal and off-nominal conditions. Identify neutron cross section data gaps and perform cross-section measurements and criticality assessments. Perform assembly level zeropower and low-power criticality measurements to validate predictions and quantify uncertainties. Establish isotopic/elemental purity requirements for all material. If fully funded, schedule reserve funding for design improvements (if required) that accommodate cross-section and neutronic performance uncertainties.



Likelihood	5	🟩	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨 2, 4	🟥	🟥
	3	🟩	🟩 3, 5	🟨 1	🟨	🟥
	2	🟩	🟩	🟨	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨
		1	2	3	4	5
		Consequence				

Figure 3.17: RXS “Top 5” Risk Ranking Likelihood and Consequence Span.

Chapter 4

Advancement Plan – CTE-2: Power Conversion Subsystem (PCS)

The Power Conversion Subsystem (PCS) converts the thermal energy from the Reactor and Coolant Subsystem (RXS) into electrical power for the NEP system. For this Technology Maturation Plan (TMP), the nominal PCS architecture is a closed Brayton cycle with recuperation, operating with a helium–xenon (He–Xe) working fluid.

4.1 Introduction

The PCS comprising CTE-2 includes a closed Brayton cycle engine consisting of turbine and compressor units, recuperator(s), radiator heat exchangers, cleanup filtration and chemical control, and piping elements, all of which are shown in green in Figure 4.1. The PCS system receives heat from the reactor (CTE-1), either directly or through a heat exchanger, and converts it to rotational mechanical power for the generator that is part of the PMAD system (CTE-3). Waste heat is rejected through the radiator system (CTE-5).

The WBS for the planned maturation of technologies in a Brayton system is shown in Figure 4.2. The turbomachinery comprising of the turbine and compressor units is the only major assembly in CTE-2 that requires focused research and development. Other component technologies, including the ducting, recuperator(s), and heat exchanger(s), will require engineering and procurement to demonstrate a modified technology which will undergo testing to verify functionality and performance of the component. Accordingly, initial focus of the proposed research and development effort is to develop, test and evaluate critical turbomachinery components. Both non-destructive and destructive evaluations will be used to demonstrate functionality of this major assembly. Concurrent detailed modeling and analysis tasks, leveraging experimental data, will be used to quantify performance scaling and reliability, and project turbomachinery lifetime over the expected duration of a mission. Components requiring only engineering development will be tested independently to verify design and functionality and then be tested as an integrated assembly with turbo-machinery components in a BrB demonstration. BrB demonstration tasks will require the design, engineering, fabrication, and assembly of the PCS for high fidelity subsystem testing. This engineering demonstration unit (EDU) will be tested to demonstrate performance and oper-

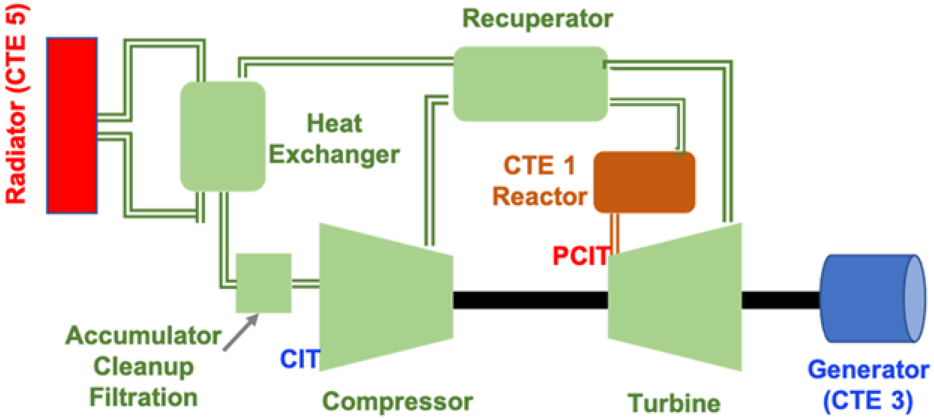


Figure 4.1: Schematic representation of the PCS. Components in green belong to CTE-2. Note that a large NEP system may possess multiple parallel copies of a PCS to produce the net electrical power required for a mission and this figure represents only one possible Brayton cycle PCS design permutation.

ated for several thousand hours, including operation at offnominal conditions, to help project overall reliability and lifetime. Finally, modeling and simulation will continue in this stage of the development. Due to the tightly coupled nature of the reactor and PCS, modeling and simulation activities and the development of instrumentation and controls systems will be integrated across the CTE-1 and CTE-2 development efforts.

Following the robust SE&I philosophy described in the Introduction, a detailed Interface Description Document (IDD) will be developed for the major external interfaces between CTE-2 and CTEs 1, 3, and 5. Preliminary descriptions of these interfaces are discussed in this section but a stand-alone IDD will be developed by SNP SMEs and provided to the SNP CTE-2 lead after discussion at the opening workshop. This IDD will be reviewed by SNP, circulated for SME evaluation if required, and then finalized and kept by the SNP SE&I lead. The document will be reviewed and revised as needed at each major relevant milestone and then reviewed as part of the NARs planned for technology advancement verification.

In addition, IDD's will be generated for internal interfaces in the PCS to ensure development work on different portions of the system are well-aligned. These IDDs will be maintained by the CTE lead and reviewed with the SNP SE&I lead and/or SMEs as needed. It is also noted that all applicable standards, including those required for human rating, will be identified and applied as appropriate so the brassboard hardware developed to achieve TRL 5 will translate to TRL 6/prototype/flight-like designs without requiring any appreciable additional research and maturation. NAR validation of this extensibility will also be a condition for technology advancement. Additionally, at the TRL 4 and TRL 5 NARs, the latest CTE-2 technology status will be combined with the latest results from the development of all the other CTEs and incorporated into a continuously-evolving conceptual vehicle configuration assessment to ensure that the combined CTEs will lead to a feasible and practical vehicle configuration.

A series of system analyses have been performed to specify KPPs for the PCS system (refs. [21, 22, 46, 88]), which resulted in the choices specified in Table 2.3. The objective

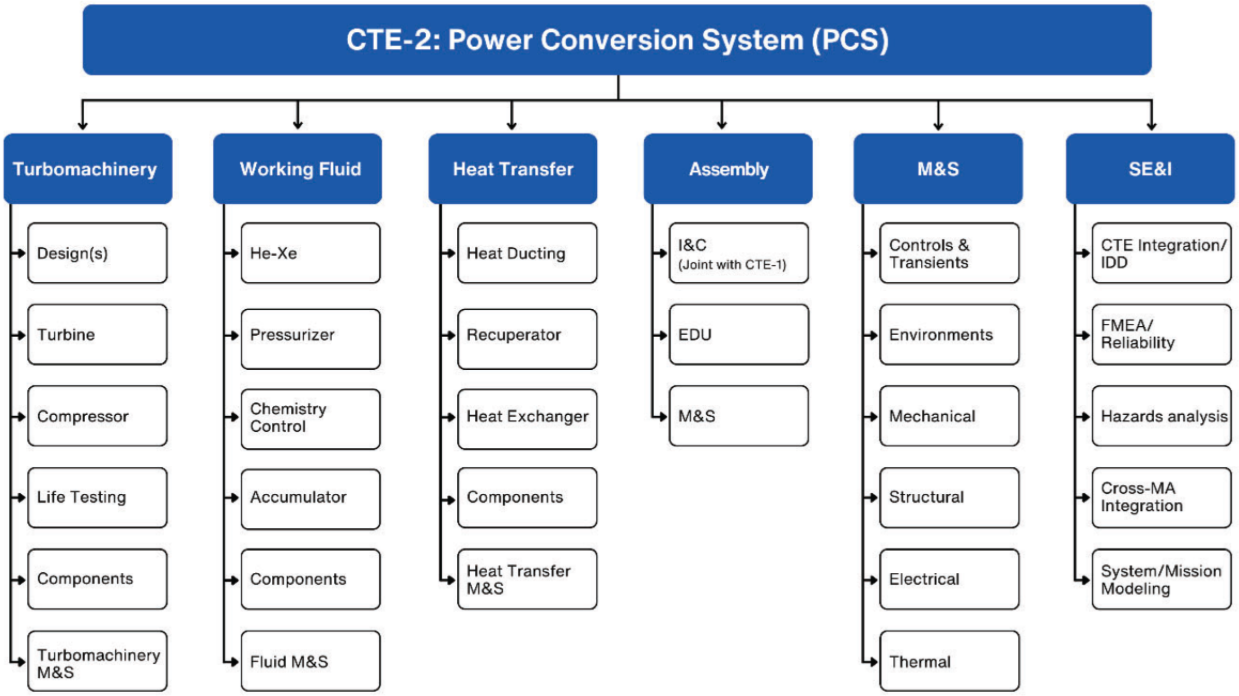


Figure 4.2: WBS for PCS subsystem development management.

of the assembly, testing, and evaluation tasks is to mature the components and assemblies of the system to the point where they can be assembled as a BrB fidelity system capable of achieving CTE-2 KPPs. As noted in Table 2.3, CTE-2 specific mass (α) estimates are preliminary and will be refined in during the maturation effort, both for CTE-2 and over the entire NEP system as development progresses. The contribution of CTE-2 to the overall nuclear electric system α is less than 10%, so the focus of this is not to develop and use new materials that might reduce the mass, but to mature technologies that yield a robust system using existing materials that meet performance requirements.

4.2 CTE-2 Power Conversion Major Assembly Technology Options Overview

The major assembly central to CTE-2 is the power conversion unit itself, which converts thermal power either directly into electrical power or into mechanical motion that can drive a power generator. For completeness, this section briefly reviews options for the power conversion unit.

Power conversion technologies relevant to space nuclear systems have been identified in a myriad of system studies and development programs at a range of power levels over decades. The most discussed power conversion technologies are:

- Static Power Conversion
  - Thermoelectric converters
  - Thermionic converters
- Dynamic Power Conversion
  - Brayton cycle engines
  - Rankine cycle engines
  - Stirling cycle engines

The level of development and the potential performance of these technologies varies widely, and as shown in Table 4.1, none have been tested to the power levels required for a MW_e-class NEP system in a relevant operating environment.

Table 4.1: Summary of Nuclear Electric Propulsion-relevant PCS technology tests. (*Thermionic Fuel Element Verification Program (TFEVP))

Concept	**Power Converter (kW_e)**	**Reactor Exit Temperature (K)**	**Efficiency (%)**	**Materials**	**Program Name and Date**
Thermoelectric	1.5	1300	4.2	Refractory	SP-100 (1993)
Thermionic	0.7	1800	9	Refractory	TFEVP* (1993)
Brayton	12	1150	20	Superalloy	Prometheus (2005)
Stirling	12	843	27	Superalloy	FSP (2015)
Rankine	150	1100	14	Refractory	SNAP-50 (1965)

Thermoelectric converters have a long history in space nuclear fission systems, particularly with the SNAP and the SP-100 program (refs. [89, 90]). Thermionic converters integrated within the reactor core were used in the Soviet TOPAZ reactors (ref. [91]). Thermoelectric and thermionic converters, however, do not scale well to megawatt electric power levels, making them unattractive options for current NEP CTE-2 development activities (ref. [92]). For example, for SP-100 program design goals (100 kW_e, 1350+ K PCIT class PCS for NEP systems), analyses showed that dynamic power conversion technology options would scale to MW_e-class performance more readily than static, solid state power conversion options (ref. [93]).

The development of Rankine cycle systems for space nuclear power applications was initiated during the 1960s as part of the SNAP reactor program. The 3.5 kW_e SNAP-2 and 35 kW_e SNAP- 8 projects focused on mercury-Rankine power conversion, whereas the 300 kW_e SNAP-50 project focused on potassium-Rankine power conversion (ref. [94]). Testing was completed in 1968 for various power plant components including life verification of the SNAP-8 mercury-Rankine subsystem and related heat transfer equipment. There have been no recent hardware development efforts related to space nuclear Rankine cycle systems and furthermore, even after significant development efforts at the time there were concerns about a lack of understanding of the two-phase flow inherent in a Rankine cycle while operating in a microgravity environment. In summary, Rankine systems are not attractive for this mission at their current state-of-readiness.

NASA is also developing and qualifying Stirling power systems for space use at unit power levels between 100 W_e and 10 kW_e (refs. [95, 96]). Most commonly used industrial-grade Stirling engines are rated between 5-10 kW_e (ref. [97]). Two high-power systems with a per-unit rating of 12.5-15 kW_e are in early development (ref. [97]). Past studies have examined Stirling cycle power generators for high-power applications and concluded that Stirling power conversion technology does not scale well for power levels higher than 100 kW_e and that it is difficult to scale individual unit power beyond 25 kW_e (ref. [98]). Using that limit, a MW_e-class NEP system would require 40 or more Stirling units.

Brayton power conversion systems have seen the most significant level of development and offer the clearest path for operating at the high temperatures, power levels, and efficiencies desired for MW_e-class NEP systems. Open-air Brayton power conversion units are routinely used in aeronautical and terrestrial applications. In an open cycle, which is not directly applicable to the NEP system, filtered outside air enters the Brayton engine, which compresses the gas, adds heat and then routes it through a turbine system to convert thermal power into mechanical motion. As shown in Figure 4.3, NEP systems require a closed Brayton cycle (CBC) engine, where the fluid flows in a continuous closed loop. Typically, a CBC system needs to operate at a higher pressure compared to an open-air Brayton system. Some of the open-air technologies and developments (such as impellers and casings) may be directly transferrable to CBC, but the higher operating pressure may mean that other components such as recuperators, seals, and bearings need customization for NEP applications. While not directly applicable, the large body of work on open-air Brayton systems does provide a large basis for understanding the performance scaling of CBC systems.

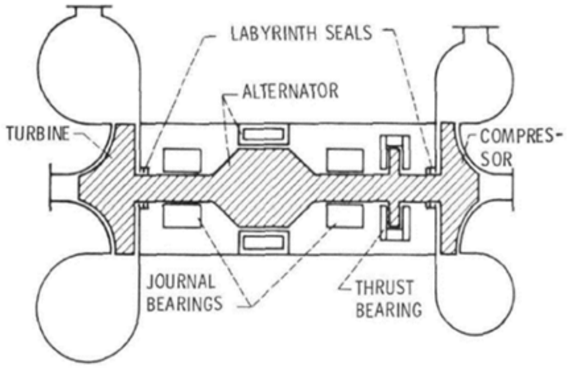


Figure 4.3: Brayton engine consisting of turbine and compressor units.

4.3 Brayton Generator System Background, State-of-Art, and Technology Gaps

This section provides a description of the current state-of-the-art and lays the groundwork for the proposed technology maturation program for a CBC power conversion system. A notional description of a Brayton engine is presented and important considerations that influence PCS performance are identified. The section concludes with a description of a turbo-machinery unit 'down-selected' for development based upon the results of current and previous development efforts.

In-space Brayton converters can be thought of as a closed-cycle version of an aircraft auxiliary power unit (APU) or gas turbine power unit (TPU). In a typical TPU, turbine and compressor are mounted on a single shaft with gas foil bearings as shown in Figure 4.3. Open cycle TPUs sized from 10-100 $\mathrm{kW_e}$ are routinely used in advanced weapon systems.

Unlike TPUs, closed cycle units typically use an inert gas working fluid, such as a He-Xe mixture, which is recirculated through a compressor and turbine coupled to a rotary alternator. Thermal input is achieved by either direct gas heating in the reactor or through an intermediate heat exchanger (CTE-1 reactor interface). The cycle working fluid is pressurized by the compressor, heated, expanded through the turbine, and cooled. A recuperator is typically employed to improve cycle efficiency using the hot turbine exhaust gas to preheat the working fluid before it returns to the heat source (in this case, the reactor). A heat exchanger transfers the Brayton waste heat to a radiator, where it is rejected to space (CTE-5 radiator interface). The turbine shaft drives the alternator/generator, which is part of CTE-3, to provide three-phase AC electrical output that is fed to the entire spacecraft through the PMAD subsystem (CTE-3 PMAD interface). In some cases, especially if the working fluid is circulated through the reactor core, a filtration and chemical control system is required to condition the fluid, removing impurities and any chemical by-products from the working fluid. This system prevents undesirable chemical interactions between the working fluid and PCS components.

NASA began closed Brayton cycle technology development in the early 1960s and this work has continued intermittently throughout the ensuing decades. The Brayton rotating unit (BRU) project (1968–1978) was aimed at a high-efficiency power conversion system for radioisotope, fission reactor, and solar receiver heat sources (ref. [99]). It was designed for operation from 2.25 to 10.5 $\mathrm{kW_e}$ depending on the charge pressure of the working fluid, at that time a He-Xe mixture with an average molecular weight of 40 g/mol. Four BRU units (Figure 4.4) were fabricated by AiResearch and tested at NASA Lewis Research Center (LeRC) (refs. [100, 101, 102]). A Brayton heat exchanger unit that combined a 95% effective gas-to-gas recuperator and a Dow- Corning 200 gas cooler was also fabricated.

The BRU system was designed for operation at a turbine inlet temperature of 1,144 K, compressor inlet temperature of 300 K, and maximum pressure of 310 kPa. The rotating assembly operated at 36 krpm and consisted of a radial in-flow turbine, centrifugal compressor, and a liquid-cooled alternator on tilt-pad bearings. The project successfully demonstrated manufacturing and assembly methods, a jacking gas startup technique, material compatibility, and high efficiency power conversion (up to 32%). The BRU turbomachinery mass was 65 kg, while the mass of the unit including recuperator and gas cooler was 200 kg.

The BRU system was also endurance tested, with one unit accumulating more than 38,000 hours of operation. While the reactor simulator heating elements failed terminating the test, the BRU operated over this time period without degradation of the moving parts. In total, the four units cumulatively amassed approximately 50,000 hours of operation, demonstrating long-life performance at the 10 $\mathrm{kW_e}$ power level. Near the end of the project, one of the units (BRU-F) was fitted with gas foil bearings and was operated at power levels up to 15 $\mathrm{kW_e}$. Subsequent CBC technology demonstration efforts for in-space use were either conducted

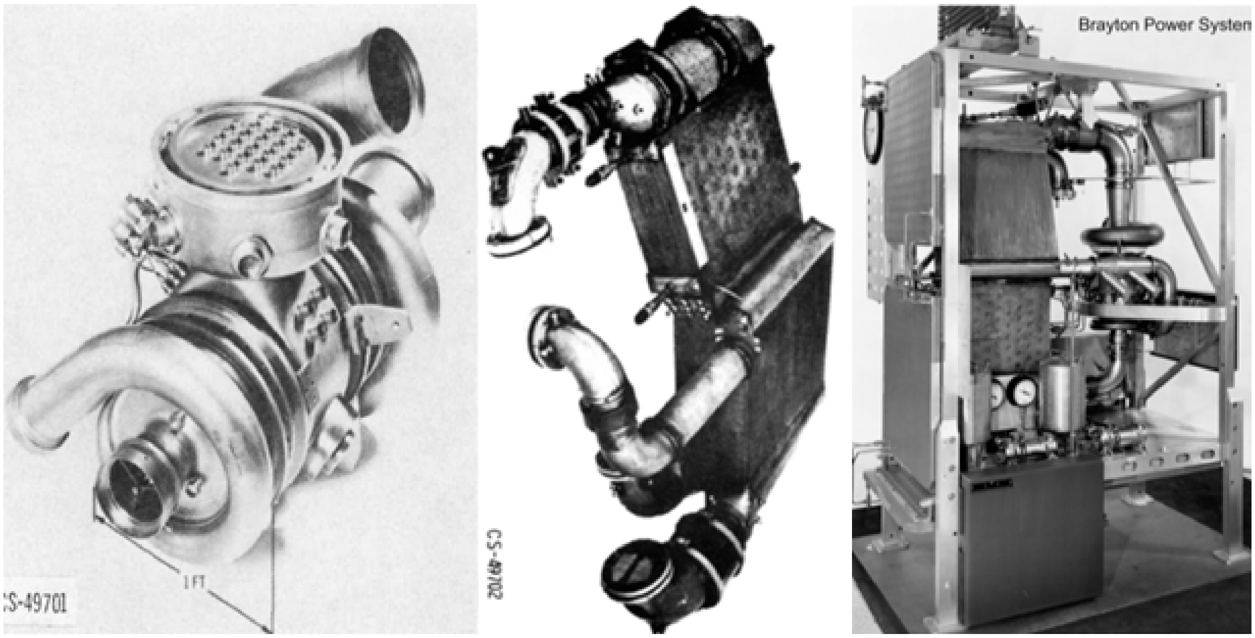


Figure 4.4: (L to R) BRU, combined recuperator/radiator heat transfer, and life testing assemblies.

at lower power for shorter durations or the work only consisted of power conversion design without any accompanying fabrication or testing.

Several industrial ventures have advanced basic Brayton cycle technology, albeit for open cycle applications. Gas foil bearings and additively manufactured impellers and turbine components have become a standard technology in APUs and TPUs. The challenge is to leverage these recent industry successes and to reestablish CBC engine technology, demonstrating it in the $\sim$1 MW_e range. Some of the important considerations follow.

Working Fluid Considerations. The working fluid is an important consideration because the molecular weight and thermal conductivity requirements will change based on the required power levels. A scoping study was performed to identify the impact of working fluid selection on CBC design and operation (ref. [41]). Shown in Figure 4.5, is the impact of compressor inlet temperature and choice of working fluid on overall system specific masses (α) when operating at a power conversion inlet temperature of 1200 K and a working fluid pressure of 10 MPa. The exact mixture composition and operating pressure will be established using modeling and simulation results that optimize performance, mass, and PCS component operating temperatures. Other analyses presented in this TMP and reference KPPs are based upon a He-Xe system at 2-4 MPa. It should be noted that trends in the α estimates are consistent with the expected behavior based upon other industry studies.

For CO_2 and sulfur dioxide (SO_2), the ideal compressor inlet temperature that minimizes system α is 600 K. For a He-Xe mixture, this temperature was found to be 500 K. Overall, our findings indicate SO_2 has the potential to provide the lowest overall system α, while He-Xe is only slightly higher (3% greater than SO_2), and CO_2 generally has the highest α (11% greater than SO_2 at their respective minima). Although SO_2 has the lowest α, it is also the least mature option, with minimal experience using this fluid in a CBC converter. For

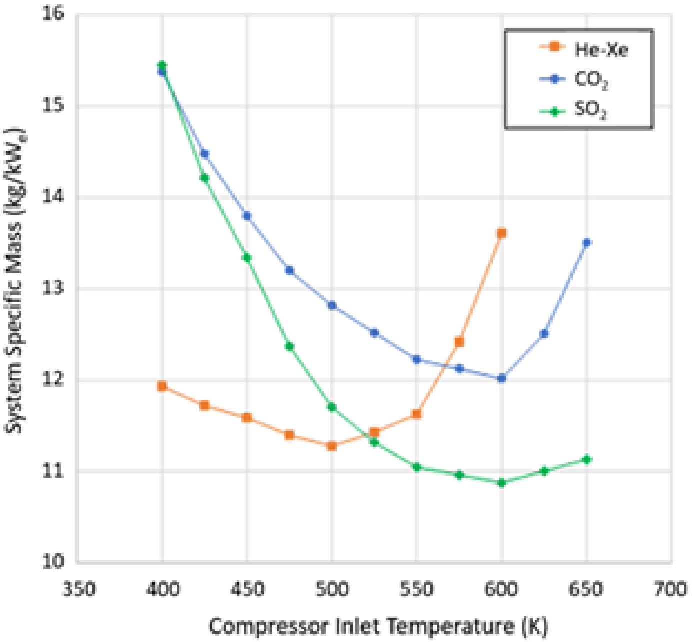


Figure 4.5: Impact of working fluid selection on NEP system alpha as a function of compressor inlet temperature (at 1200 K PCIT and 10 MPa working fluid pressure) (refs. [41, 103]).

both SO_2 and CO_2, corrosion and long-term fluid stability are potential challenges requiring study. These factors may ultimately require more exotic materials for SO_2 or CO_2, and/or may limit the maximum PCIT. Conversely, He-Xe is an inert gas mixture that can operate at high temperatures, is not susceptible to corrosion or fluid degradation, and has already demonstrated long-term operation in CBC converters developed for spaceflight. Although α of a He-Xe system is slightly greater than SO_2, the significant uncertainty regarding potential issues associated with SO_2 drove the decision to focus technology maturation efforts on He-Xe. In addition, a He-Xe working fluid is attractive because it reduces the required shaft speed. For these reasons, He-Xe working fluid is baselined for this technology maturation project.

Power Conversion Inlet Temperature Considerations. The Brayton PCIT is another critical parameter of the system. The optimized radiator area as a function of compressor inlet temperature for two separate PCIT values is shown in Figure 4.6. These data show that radiator size, and the commensurate mass contribution to the overall power system α is substantially reduced when increasing the PCIT from 1200 to 1400 K. The fractional contributions of different CTEs to power system α are given in Figure 4.7 for the optimum parameters in Figure 4.8 (as indicated by the red dashed line). The reduction in radiator size associated with the higher PCIT results in a lowering of power system α by 20%. Tied to this trade-off is the power conversion efficiency. There exists an optimal efficiency value where the most electrical power per unit mass of the system is extracted from the thermal power of the system. The optimum efficiency is a balance between the working fluid temperature drop resulting from the conversion of reactor heat to electricity and the desire to maintain a relatively high turbine exit temperature so the radiator (downstream of the turbine) will still be rejecting heat at a high-enough temperature to minimize its overall contribution to system mass.

Clearly, selecting the optimal temperature, working fluid, pressure, and power conversion efficiency are key design factors, and setting these values (especially the temperature values in the system) early in the process will drive optimization of system α and performance. Achieving these values will depend upon the ability of the selected materials to support the desired temperatures. Based on industry TIMs combined with preliminary analyses (ref. [30]), a threshold PCIT of 1200 K is established; this value is in-line with demonstrated BRU operating temperature (1140 K). Most turbo-machinery materials, such as oxide dispersion-strengthened (ODS) steels and superalloys, are qualified to this threshold temperature and thus this option minimizes technology risk. On the other hand, current state-of-the-art suggests that operation at 1400 K is likely feasible and operating at this temperature can provide significant system-level benefits for NEP vehicles. One option is to use materials capable of operating at higher temperatures in the turbine and ducting. A second option, which has not been explored to date in space power conversion systems but has been used extensively in gas turbine/jet engine applications, is the use of film cooling. While this may result in a minor efficiency reduction, achieving a PCIT of 1400 K or greater has the potential for a large and beneficial system-level mass reduction.

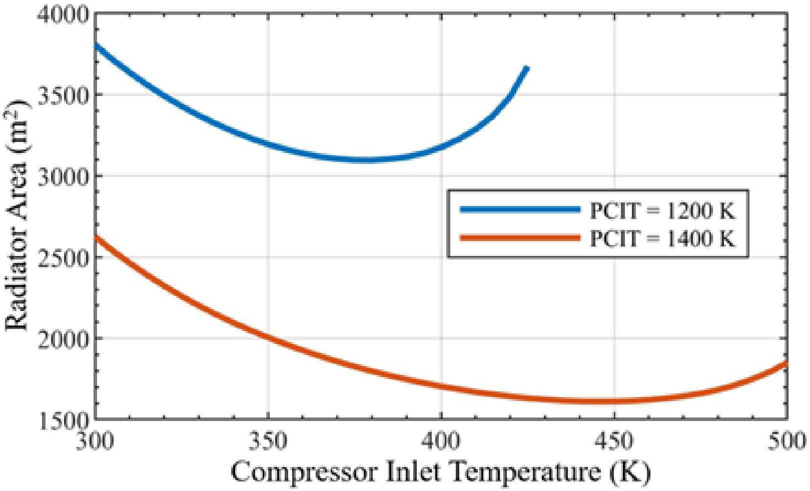


Figure 4.6: Impact of power conversion inlet temperature on single-loop radiator size at 1 MPa with He-Xe (ref. [41]).

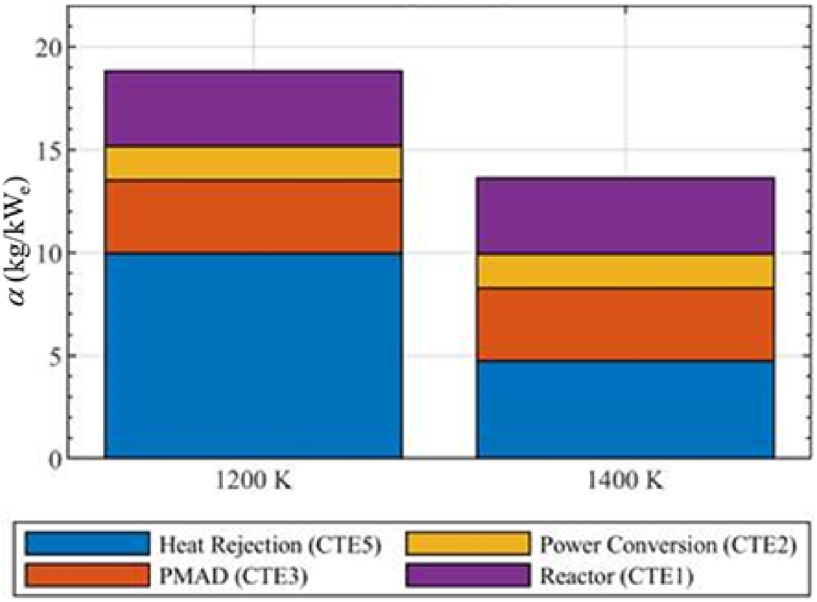


Figure 4.7: Impact of PCIT on PCS α and subsystem contributions to α for He-Xe. PCS working fluid at 1 MPa using the optimum radiator area cases of Figure 4.6 (ref. [41]).

The focus of proposed technology maturation activities is to target 1400 K operation, but quickly down-select to the low-risk threshold option if the perceived risk is too high. At the present, mission studies have shown that for opposition-class human Mars missions, both the threshold and target options meet mission α requirements (refs. [21, 22, 41, 103]).

Unit Power Level Considerations. At power levels below approximately 100 kW$_e$, Brayton cycle technology becomes less efficient due to higher relative tip clearances and high rotational speed windage losses. The maximum rotational speeds of the compressor, turbine, and generator as a function of cycle power are shown as lines in Figure 4.8 (top). These maxima decrease as a function of power, but the generator maximum (dashed line) decreases more rapidly than the remainder of the turbomachinery (assuming a standard three-phase induction generator). The rotational limits are due to three factors: mass flow rate, turbine stresses, and rotor stresses. However, there is a significant weight reduction of this system when the rotational speed is maximized because power is directly related to speed and/or frequency. The turbomachinery has an optimal range of performance that is a function of the loading, flow rate, and specific speed but generally higher rotational speeds, which are beneficial, are limited by keeping the blade tip speed to be subsonic and limiting structural stress at the blade root. The generator speed is primarily limited by the topology being used. For example, an induction or permanent magnet generator has a lower stress limit than a switched reluctance generator, which is only comprised of rotating steel as opposed to magnets or coils. It is possible to separate the generator rotational speed from the turbomachinery rotational speed by using two turbines on separate shafts, but that adds control complexity. In all cases, maximizing the rotational speeds while maintaining structural limits results in a more compact turbo generator system.

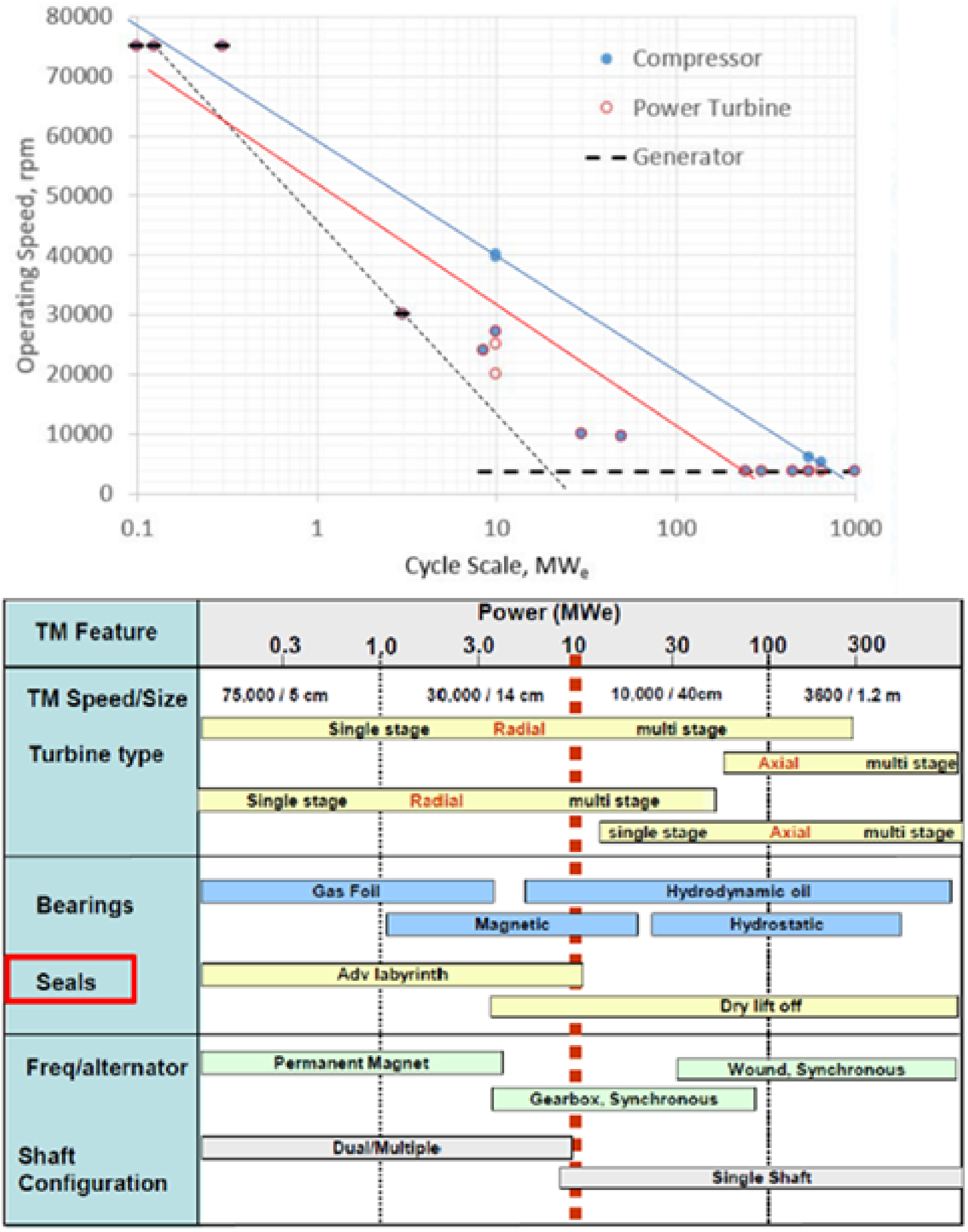


Figure 4.8: Power converter and generator integration considerations. Top: Optimal turbomachinery component rotational speeds as a function of cycle power. Bottom: Impact of power level on component design options (ref. [41]).

Figure 4.8 (bottom) further shows that the required power level also factors into multiple design choices for the turbomachinery. The topology options include the choice of compressor and turbine blade types, number of compressor and turbine stages, bearings, seals, shaft configuration, and alternator coupling. For systems above 10 $\mathrm{MW_e}$, the required mass flow rates result in larger and slower rotating systems with multiple axial compressor and turbine blade rows, as is commonly found in aircraft engines and terrestrial power plants. For NEP power generation, with Brayton generators producing between 0.5-1.0 MW_e each, the systems optimize using single-stage radial compressors and turbines. Moreover, since this is a space application the system is closed to the environment and the choice of working fluid can be optimized to further improve the efficiency and unit power density. This also favors the use of non-contact, non-lubricated gas bearings on shaft rotating at 50,000 rpm or greater. System complexity can be reduced to a single rotating component, with the generator installed directly on the same shaft as the compressor and turbine. Permanent magnet-based alternators are currently the most typical class of devices considered, but more recent developments in power electronics have enabled the use of a higher-speed and more robust switched reluctance configuration. It should be noted that multiple closed Brayton cycle generator units can be configured to either operate in parallel or in series, sharing the same flow to further increase the power, specific power, and efficiency of the system.

Brayton Turbo-Machinery System Selected for Technology Maturation. The team selected 1200 K superalloy Brayton (SAB) and 1400 K refractory alloy-based Brayton (RAB) power generation as the most likely power generation technology options for a high-power NEP system. As described previously, another option that could enable a power conversion inlet temperature of 1400 K or greater is the use of film cooling, which is the state-of-the-art for jet engine turbine blades and has a long history of implementation in that field. As discussed above, Brayton cycle systems operating at these temperatures have been shown to close the NEP human Mars opposition-class mission in preliminary evaluations. Figure 4.9 illustrates a CBC system with a single stage turbine and compressor that uses a He-Xe working fluid operating at pressures in the range of 2–3 MPa. A unit would be sized to produce between 0.5 and 1 MW_e, which minimizes the necessary technology development activities for the generator while achieving the KPPs listed in Table 4.2. Various other attractive features are as follows:

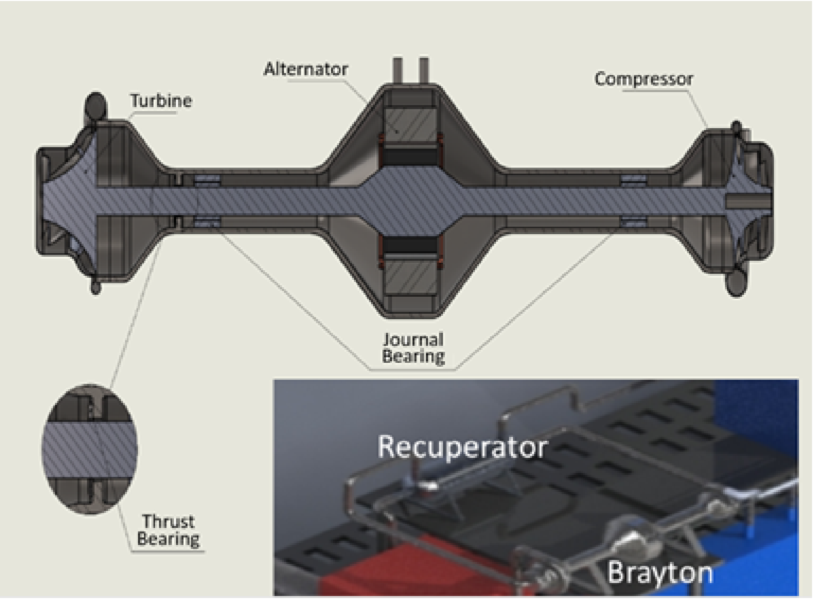


Figure 4.9: 500 kW_e He-Xe Brayton Power Conversion Unit.

- **High Efficiency**: Brayton systems are the established cycle for high efficiency, high-power generation in terrestrial power production and aircraft turbofan applications. CBCs have the additional advantage of a recuperator for increased efficiency. The system is heated by the nuclear heat source, which avoids combustion gas fouling that occurs in some terrestrial gas turbine applications.

- **Long Life**: At or below the 1 MW_e power level, non-contacting, non-lubricated gas bearings can be used. The noble gases comprising the He-Xe mixture do not react with the engine materials. For these conditions, the major possible failure mechanisms are creep failure of the turbine blades and turbine. At or below 1200 K, superalloy material properties (including Larsen-Miller curves) are well-known, enabling modeling of the materials during operation. Material property data gaps may exist for refractory alloys up to and beyond 1400 K.

- **High-power**: The He volume fraction and pressure of the working fluid can be adjusted to support a wide range of power levels and the heat exchangers can be scaled to required sizes since they are external to the turbomachinery. The optimal proportion of He to Xe increases to unity as the power level increases to 5 MW_e and beyond.

- **High Voltage**: The relatively high-speed rotating shaft enables efficient high voltage power generation in the alternator/generator of CTE-3, reducing the need for heavy power conversion and transformer hardware in the design of CTE-3.

- **Compact**: As a point of reference, a 500 kW_e Brayton power conversion unit (Figure 4.9) is approximately two feet in length and the compressor and turbine are roughly six inches in diameter.

- **Heritage**: Significant terrestrial and aircraft turbine development has resulted in many validated design tools. For CBC systems, however, there have only been a limited number of experimentally demonstrated designs.

Table 4.2: KPP Guidance for CTE-2 Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Power Conversion Inlet Temperature (PCIT)	1200 K	1400 K	Operation at 1400 significantly reduces radiator α while simultaneously increasing PCS efficiency.
Thermal efficiency	40% of Carnot efficiency (e.g., 25% at 1200/450 K)	52% of Carnot efficiency (e.g., 40% at 1400/323 K)	Increased thermal efficiency reduces the amount of waste heat that must be rejected from the NEP system and reduces the thermal power requirements of the reactor (CTE-1). Thermal efficiency is dependent upon the thermodynamic efficiency of the PCS design and CTE-2 interfaces with other subsystems.
CTE-2 α kg/kW_e)	3	2	Threshold and target α parameters are derived from mission analysis. Current models estimate that CTE-2 contribution to the overall alpha is $\sim$10%. These values are preliminary and subject to revision as the overall achievable system α is better quantified.
KPP	**Range**		**Significance**
Total Subsystem Power/Per Unit Power (MW_e)	2-4 / 0.5-1		Ranges are indicative of evolving mission needs. System will likely use multiple PCS units each ranging from 0.5 – 1.0 MW_e.
Compressor Inlet Temperature (CIT)	320-450 K		Efficiency and radiator materials selection influenced temperature range. *CIT is provided for the thermal efficiency KPP as reference only.
Lifetime (hours)	25,000	32,000	Human Mars mission is estimated to be 20,000–30,000 hrs of operation.

4.4 PCS Technology Advancement Plans

The SNP project technology maturation plan is a methodical approach to the advancement of the PCS system (CTE-2) to the TRL 5 in a 4-year time period. At present, no design for a $\mathrm{MW_e}$-class CBC unit exists. The first step of TMP is the development of a qualifiable design with particular emphasis on manufacturability using existing materials and technologies where possible. The research and development program focuses on achieving BrB level hardware fidelity and performing extended endurance testing supported by various M&S efforts, including failure mode quantification efforts.

The identified gaps and proposed maturation approach are consistent with the recommendations from recent NASA funded space nuclear propulsion studies The recommendation from the NASEM study (ref. [29]) is “NASA should rely on (1) extensive investments in modeling and simulation, [and] (2) ground testing (including modular subsystem tests at **full-scale and power**).” (emphasis added) The intent of long duration testing is to operate for sufficient time to permit quantification of system life.

Table 4.3 lists major Brayton PCS components, with a brief description of the advancements needed to mature each to TRL 5 (minimum) during a 4-year development program. More detail on the development effort, risks, and risk mitigation plans associated with these efforts are provided in the following sections.

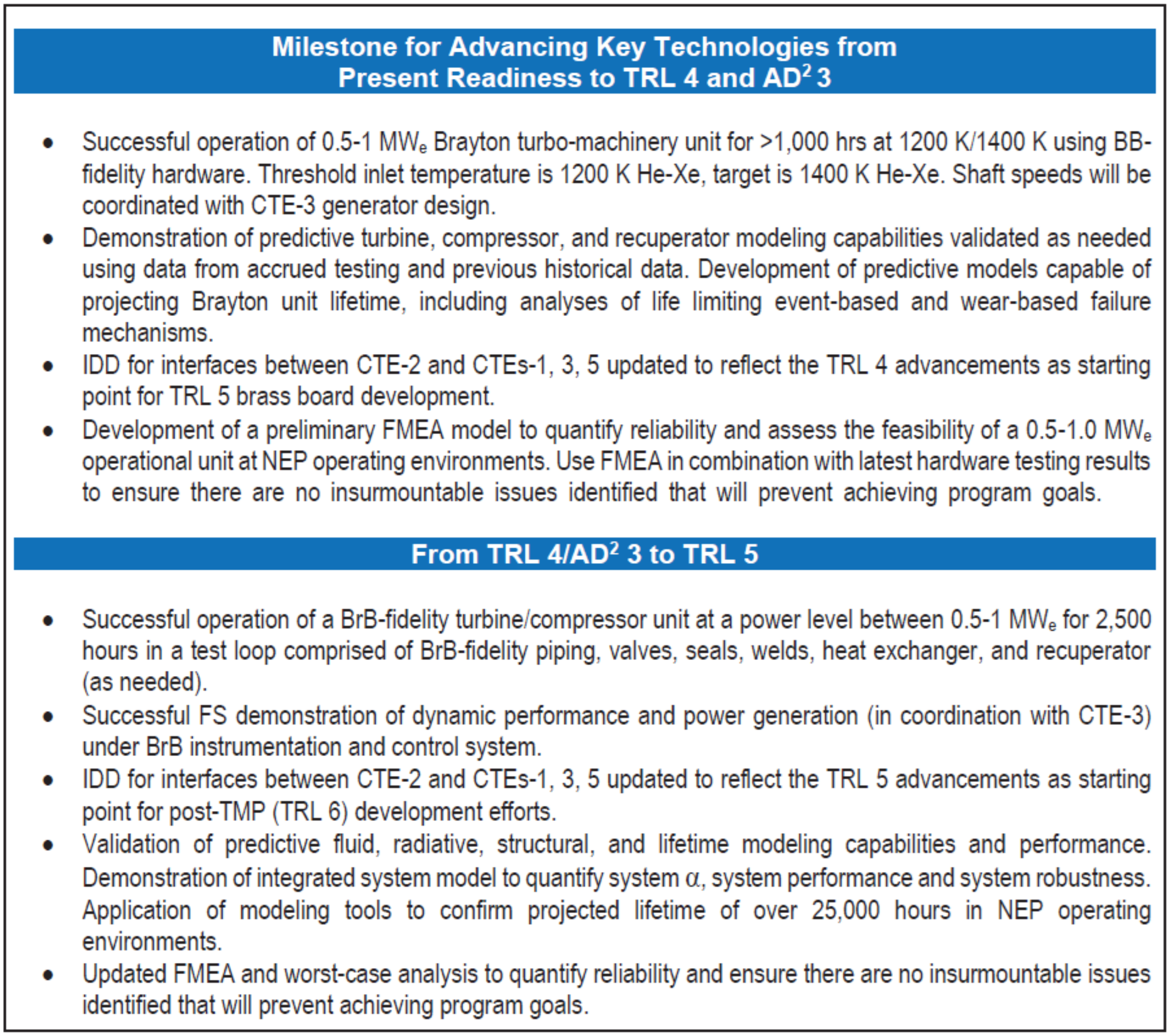
Table 4.3: CTE-2 Major Technology Aspects and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Overall Performance and Interfaces	Design a turbine/compressor system including explicit identification of interfaces and performance requirements. Design assessments will also include evaluation of manufacturability of the integrated PCS.
2	Turbine	Demonstrate long endurance operation of a turbine/compressor system at a high PCIT (1200-1400 K) at a power level between 0.5-1.0 $\mathrm{MW_e}$. Final testing will be performed using BrB fidelity hardware, quantifying α ($\mathrm{kg/kW_e}$) while operating under nominal design pressure and temperature conditions for up to 2,500 hours. In addition to nominal operation, testing will include evaluation under various expected transient conditions. Measured parameters will include efficiencies, compression ratios, and other data necessary to validate component and subsystem models. A predictive model, including transient subsystem/component models and FMEA, will be developed and validated to project life to >25,000 hours.
3	Compressor	
4	Working Fluid	Develop a chemical, material, and irradiation compatibility data base for a He-Xe working fluid, validated for target operating environments.

Table 4.3: CTE-2 Major Technology Aspects and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
5	Recuperator	These components are in wide use commercially, though commercial heritage so far is limited to open air and lower (∼1100 K) operating temperatures. Key advancement challenge is to demonstrate feasibility of constructing these components with low-α materials that can withstand operating pressure and temperature conditions through BrB tests. Extending existing technologies to the threshold conditions (1200 K and 2-3 MPa) will require design, engineering and fabrication effort. Extending operation to 1400 K at the
6	Ducting and Valving	
7	Accumulators and Pressurizer	moderate pressure (2-3 Mpa) may require additional development efforts, such as focused materials selection and fabrication methods consistent with short mission time (3-years). Tasks in the early phase will enable a decision on whether to pursue threshold or target options. A key research and development effort may include use of stand-off sensing to continually monitor structural health of the PCS loop to identify off-nominal performance during incipience of failure and provide a means to protect against catastrophic outcomes.
8	Heat Exchangers	
9	Modeling and Simulation	Develop, validate, and apply joint CTE-1 /CTE-2 models that (1) provide upper & lower bounds on achievable performance & mass KPPs; (2) are capable of modeling startup, restart, transient & hot-standby cases; (3) can assess the ability of the system to withstand off-nominal (e.g., thruster out) conditions; (4) can model and demonstrate effectiveness of the control architecture; and (5) can assess failure modes and effects to characterize system reliability and robustness.

Overall, the project plan progresses through a series of hardware tests and model development cycles to advance technology readiness in a stepwise fashion with respect to the level of hardware fidelity and power handling capability. Demonstration of TRL 5 for the PCS will include fabrication and endurance testing (2,500-hours) BrB-fidelity Brayton PCS unit. BrB fidelity system testing will include critical event testing and quantification of wear-based life limiting mechanisms specific to the NEP PCS projected mission concept of operations and operating parameters of temperature, pressure, working fluid, and PCS power level. Detailed component structural models will be developed and validated from testing data to project reliability against potential life-limiting creep and corrosion effects. Coupling component and system testing with M&S efforts supports power conversion system integration with the spacecraft and allows for projections of the required lifetime with as much validation from sub-scale to full-scale ground testing as possible in the time available. Hardware development is limited to the turbomachinery and I&C systems that monitor CTE-2 performance. The remainder of the auxiliary components, such as piping, recuperators and heat exchangers will be procured as necessary to facilitate engineering demonstration. In the proposed design, the generator rotor is affixed directly to the CBC shaft with no intermediate coupler (e.g., gearbox). Given the anticipated rotating speed (30+ krpm) and generator load, it is highly likely that the CTE-2 and CTE-3 generator development efforts will be coupled and that a fully functional generator could be used for joint functional and endurance BrB-fidelity testing. A reactor simulator will be developed in conjunction with CTE-1 to drive the PCS. Discussions with SMEs have resulted in SNP setting the following criteria for advancement of PCS technologies (Figure 4.10).



Milestone for Advancing Key Technologies from Present Readiness to TRL 4 and AD^2 3

- Successful operation of 0.5-1 MW_e Brayton turbo-machinery unit for >1,000 hrs at 1200 K/1400 K using BB-fidelity hardware. Threshold inlet temperature is 1200 K He-Xe, target is 1400 K He-Xe. Shaft speeds will be coordinated with CTE-3 generator design.
- Demonstration of predictive turbine, compressor, and recuperator modeling capabilities validated as needed using data from accrued testing and previous historical data. Development of predictive models capable of projecting Brayton unit lifetime, including analyses of life limiting event-based and wear-based failure mechanisms.
- IDD for interfaces between CTE-2 and CTEs-1, 3, 5 updated to reflect the TRL 4 advancements as starting point for TRL 5 brass board development.
- Development of a preliminary FMEA model to quantify reliability and assess the feasibility of a 0.5-1.0 MW_e operational unit at NEP operating environments. Use FMEA in combination with latest hardware testing results to ensure there are no insurmountable issues identified that will prevent achieving program goals.

From TRL 4/AD^2 3 to TRL 5

- Successful operation of a BrB-fidelity turbine/compressor unit at a power level between 0.5-1 MW_e for 2,500 hours in a test loop comprised of BrB-fidelity piping, valves, seals, welds, heat exchanger, and recuperator (as needed).
- Successful FS demonstration of dynamic performance and power generation (in coordination with CTE-3) under BrB instrumentation and control system.
- IDD for interfaces between CTE-2 and CTEs-1, 3, 5 updated to reflect the TRL 5 advancements as starting point for post-TMP (TRL 6) development efforts.
- Validation of predictive fluid, radiative, structural, and lifetime modeling capabilities and performance. Demonstration of integrated system model to quantify system α, system performance and system robustness. Application of modeling tools to confirm projected lifetime of over 25,000 hours in NEP operating environments.
- Updated FMEA and worst-case analysis to quantify reliability and ensure there are no insurmountable issues identified that will prevent achieving program goals.

Figure 4.10: Key Milestones in the CTE-2 PCS Advancement Strategy.

Tables 4.4 through 4.7 describe tasks proposed in this effort to achieve milestones in Figure 4.10. It commences (Table 4.4) with a design effort to evaluate approaches for leveraging current industry state-of-the-art in turbomachinery to arrive at a baseline closed Brayton cycle PCS design for NEP. This assessment will provide further confidence in the proposed development approach. The activities described in Table 4.5 are aimed at acquiring materials data necessary to adapt current industry state-of-the-art technologies and designs to the NEP application and performing a BB-fidelity test of PCS hardware. These activities address data gaps such as irradiation effects on seals, bearings, and welds and the quantification of creep, corrosion, and erosion of base materials while operating at temperatures and pressures expected for a highpower NEP mission. Data from materials characterization are vital for projecting turbomachinery reliability over a required mission lifetime. The third set of activities, listed in Table 4.6, describe the component modeling and simulation effort with a particular focus on the turbomachinery components. The objective here is to extend industry-standard advanced modeling tools (such as those used in performing Table 4.4 tasks) to accurately capture important lifelimiting mechanisms of relevance to an NEP mission. A series of validation studies will be executed using industry data on the APUs and TPUs as a starting point. Models will be used for pre-test predictions and will be adjusted as needed using early post-test data. The final set of activities, listed in Table 4.7, describe BrB-fidelity hardware development, assembly of an EDU and performance and endurance testing.

Table 4.4: PCS CTE-2 Component Maturation Path for Design Maturity Advancement.

Major Technology Milestones	**#**	**Timeframe (End Date)**	**Significance**
SME Workshop	CTE2-1.1	Q1/Y1	Participation in opening NEP SME workshop to ensure planned component maturation paths are compatible with related major assembly and subsystem hardware and M&S development efforts and understanding of inputs required to support CTE-level IDD, FMEA, and hazard and risk list development efforts.

Table 4.4: PCS CTE-2 Component Maturation Path for Design Maturity Advancement.

Major Technology Milestones	**#**	**Timeframe (End Date)**	**Significance**
Conceptual component level major assembly design	CTE2-1.2	Q2/Y1	Material Selection, Identification of Interfaces, Operating Conditions Predicted, Knowledge Gaps Identified, Possible Component Fabrication Methods Identified He-Xe PCS modelling: Assess He-Xe PCS for different turbine inlet temperatures and PCS configurations to bound the design space of the PCS configuration for BB hardware fabrication and testing. Threshold is 1200 K He-Xe in a single stage turbine. Target is 1400 K He-Xe in a single stage turbine. Perform trade studies that quantify advantages and risks posed by different design permutations, including but not limited to the use of high efficiency recuperators, multi-stage turbines, and active cooling schemes. Preliminary risks and hazards lists generated. Draft FMEA created.
Facilities and scalability assessment studies complete	CTE2-1.3	Q3/Y1	Identification of available facilities and components to support BrB EDU testing and required modifications and interface emulators to enable testing under desired BrB test conditions.
Operating conditions: for Brayton turbine testing selected	CTE2-1.4	Q4/Y1	SNP SME assessment of available information to finalize decision on to use threshold or target operating conditions (temperature and pressure) and gas mixture composition for CTE-2 demonstration.

Based on the required technology maturation activities presented in prior sections, a schedule for PCS technology development is presented in Figure 4.11. The schedule is structured to reflect the four major activities presented in Tables 4.4 through 4.7, PCS conceptual design, PCS hardware advancement to TRL 4 (BB), PCS M&S activities, and PCS hardware advancement to TRL 5 (BrB). For each of these activities, major tasks and durations are included in the figure and all milestones are included in the figure as indicated by the diamonds. In summary, initial tests require the development and analysis of a PCS system to develop component designs as well as understand subsystem scaling parameters to inform facilities requirements or potential modifications to support all phases of planned testing. Modeling and simulation advancement is also anticipated, which will proceed in parallel to component design and testing and will be validated with the test data generated throughout the planned development program. The first phase of design, fabrication, and testing is focused on the component level to mature new turbomachinery technologies and confirm the performance of procured components at a BB level of fidelity appropriate for TRL 4 and AD^2 3. This phase is planned to last approximately 30 months including post-test inspection activities. The second phase of design, fabrication, testing activities is BrB testing of a PCS subsystem under various conditions to demonstrate the subsystem under all parameters which satisfy definitions for TRL 5. Not including facilities modifications, BrB testing is anticipated to span a duration of 24 months with some overlap with the TRL 4advancement activities. For each test, a TCR and MVR are planned to ensure test objectives were satisfied and gathered test data are capable of use for model validation. At the end of each design-build-test phase, a NAR is planned to gather a team of non-advocate experts who will review the outcome of the fabrication and testing activities and assess whether advancement criteria have been met. It is noted that if iterative development is needed during each of the phases to meet advancement criteria, the schedule will be adversely impacted.

For example, during TRL 4 advancement activities, if a component does not meet success criteria and requires iterative development, not all components will be ready for BrB testing and the BrB advancement task phase may be delayed. Another schedule assumption which will require refinement based on the exact design solution, especially for components that are engineered and procured external to the project, are design and fabrication task durations which are assumed for this schedule to last 6 and 9 months respectively for all components.

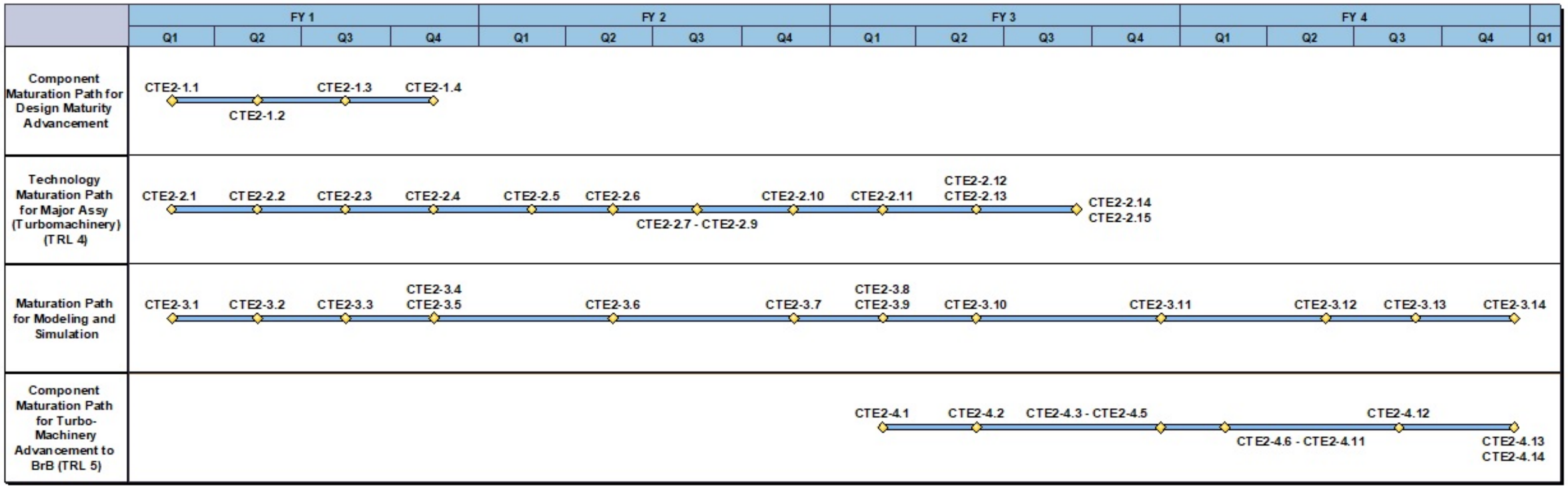


Figure 4.11: CTE 2 Advancement Schedule

Table 4.5: CTE-2 Technology Maturation Path for Major Assembly (Turbomachinery) Advancement to BreadBoard Fidelity (TRL 4).

Major Technology Milestones (Bread Board – TRL 4)	**#**	**Timeframe (End Date)**	**Significance**
SME Workshop	CTE2-2.1	Q1/Y1	Participation in opening SME workshop to ensure 1) planned turbomachinery maturation path is compatible with related major assembly and subsystem hardware and M&S development efforts and 2) understanding of inputs required to support CTE-level IDD, FMEA, and hazard and risk list development efforts.
Initial IDD, FMEA, and hazard and risk list inputs delivered	CTE2-2.2	Q2/Y1	Inputs to support CTE-level IDD, FMEA, and hazard and risk list development complete.
Definition of material and component property requirements and test plans for validation (including irradiation) complete	CTE2-2.3	Q3/Y1	Enables both selection of materials and component designs for TRL-4 hardware testing and test plan finalization.
Quantification of material and component properties through testing of representative material coupons or components.	CTE2-2.4	Q4/Y1	Provides required thermal and mechanical material properties to fill existing gaps prior to major hardware developments. Testing to bound expected range of operating conditions (e.g., atmosphere, pressure, temperature, and lifetime) with margin.
BB turbomachinery design complete with SNP internal design review	CTE2-2.5	Q1/Y2	BB design evaluated by SNP SME (and others as necessary) and ready for fabrication.
Design of test article for steady-state irradiation testing complete with SNP internal review.	CTE2-2.6	Q2/Y2	Irradiation test article design evaluated by SNP SME (and others as necessary) and ready for fabrication.

Table 4.5: CTE-2 Technology Maturation Path for Major Assembly (Turbomachinery) Advancement to BreadBoard Fidelity (TRL 4).

Major Technology Milestones (Bread Board – TRL 4)	**#**	**Timeframe (End Date)**	**Significance**
BB turbomachinery test article fabrication, inspection, and installation complete	CTE2-2.7	Q3/Y2	Test article acquired and installed for 1000-hour testing.
1000-hour Non-Nuclear BB turbomachinery TRR	CTE2-2.8	Q3/Y2	SNP review of the 1000-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures. Coordinate with CTE-3 to ensure generator design is consistent with CTE-2 test objectives.
Irradiance test article fabrication, inspection, and installation complete	CTE2-2.9	Q3/Y2	Test article acquired and installed for 1000-hour testing.
Irradiation performance TRR	CTE2-2.10	Q4/Y2	Perform a peer review of the test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures for irradiation testing.
1000-hour non-nuclear turbomachinery test complete	CTE2-2.11	Q1/Y3	BB turbomachinery test demonstrates performance under laboratory conditions - all required data on chemical and thermodynamic compatibility of components at projected NEP operating conditions obtained.
Steady state irradiation testing complete	CTE2-2.12	Q2/Y3	Irradiation data gaps closed to permit downselect between material options for components key components such as bearings and seals and working fluids (e.g., required knowledge of radiolysis, gas generation, and/or activation rates obtained).
Internal turbomachinery test review (TCR & MVR)	CTE2-2.13	Q2/Y3	SNP assessment of all test results to complete the required model validation and generate a plan for future model advancements. Inputs for external NAR generated including test data-based hardware assessments and draft IDD, FMEA, and hazard and risk lists.
TRL/AD^2 Advancement NAR	CTE2-2.14	Q3/Y3	NAR for advancement of turbomachinery to TRL 4 – acknowledgement that all milestones were met.

Table 4.5: CTE-2 Technology Maturation Path for Major Assembly (Turbomachinery) Advancement to BreadBoard Fidelity (TRL 4).

Major Technology Milestones (Bread Board – TRL 4)	**#**	**Timeframe (End Date)**	**Significance**
Updated IDD, FMEA, and risk & hazards lists complete.	CTE2-2.15	Q3/Y3	IDD revised as necessary for BrB emulator development. Revisions to FMEA, and risks & hazards completed and delivered to SNP.

Table 4.6: PCS CTE-2 Maturation Path for Modeling and Simulation.

Major M&S Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Initial workshop	CTE2-3.1	Q1/Y1	Participation in opening SME workshop to ensure planned M&S development efforts are sufficient to support hardware development and validation efforts.
Component model development plans complete	CTE2-3.2	Q2/Y1	Specifies requirements for component level models for turbomachinery for NEP applications. Models for performance, creep, lifetime, and transient analysis are needed. All available data from creep and corrosion measurements from parallel experimental activity gathered for input to model development efforts. Validate turbomachinery component models using existing TPU and APU testing (including sponsoring selected new tests).
Initial power system framework for integration of CTE-2 models with CTEs -1, -3, -5 models developed.	CTE2-3.3	Q3/Y1	Framework to integrate M&S efforts spanning key power generation, transmission, and heat rejection CTEs in place for reference/consideration in all CTE-2 M&S development efforts.
Preliminary turbomachinery component models complete with plans for next generation.	CTE2-3.4	Q4/Y1	Modifications to existing turbomachinery component models complete using literature data and data generated in component and BB turbomachinery testing. Gaps in existing data identified and specific plans for required testing generated (for inclusion in hardware development test planning).

Table 4.6: PCS CTE-2 Maturation Path for Modeling and Simulation.

Major M&S Milestones to TRL 5	#	**Timeframe (End Date)**	**Significance**
Integrated (major assembly-specific) modeling plan in place.	CTE2-3.5	Q4/Y1	Detailed plan for CTE-2 M&S (steady state & transient) advancement in place with tools selected, gaps/paths defined, major risks identified, and mitigation plans in place.
Initial integrated power system model complete with SME review.	CTE2-3.6	Q2/Y2	Preliminary end-to-end modeling of the integrated power system complete using all available data on relevant physical properties and heat transfer correlations for a He-Xe system and including instrumentation and control sub-models for remote operation (i.e., semi-autonomous operation logic).
Initial integrated steady state power system model validation.	CTE2-3.7	Q4/Y2	End-to-end model exercised and compared against steady state data from BB turbomachinery testing and from testing performed in other projects (e.g., Project Pele (HTGR) and/or other micro-reactor testbeds). Shortfalls identified for advanced (nominal & transient) model development.
Initial integrated transient power system model validation.	CTE2-3.8	Q1/Y3	End-to-end model exercised and compared against steady state data from BB turbomachinery testing and from testing performed in other projects (e.g., Project Pele (HTGR) and/or other micro-reactor testbeds). Shortfalls identified for advanced (nominal & transient) model development.
Preliminary FMEA & uncertainty quantification (UQ) complete.	CTE2-3.9	Q1/Y3	Documents provide 1) specific inputs required for TRL 4 CTE-level FMEA and hazards and risk lists and 2) SME-generated recommendations for required modifications/additions for the BrB phase.
M&S advancement plan for TRL 5/BrB testing phase complete.	CTE2-3.10	Q2/Y3	SME generated plan for model improvements developed (based on findings from TRL 4 advancement findings) and ready for TRL 5-phase implementation.
Revised nominal and transient model(s) developed (pre-BrB testing).	CTE2-3.11	Q4/Y3	M&S tool suite updated and available to generate outputs for comparison with BrB hardware testing in Y4 – SNP ready to implement predict-compare-predict iterative cycles to refine/validate model.

Table 4.6: PCS CTE-2 Maturation Path for Modeling and Simulation.

Major M&S Milestones to TRL 5	#	**Timeframe (End Date)**	**Significance**
Initial nominal & transient model exercise/review in BrB test phase	CTE2-3.12	Q2/Y4	CTE-2 performance & transient model exercised based on BrB testing – SME review to identify shortfalls and mitigation strategies.
Final nominal & transient model validation in BrB test phase	CTE2-3.13	Q3/Y4	CTE-2 performance & transient model exercised based on BrB testing – SME review with comments for final modifications.
Final model revisions complete – delivered to SNP.	CTE2-3.14	Q4/Y4	Final model delivered to SNP for use to support advanced development (Post TRL 5). Deliverables to include all model descriptions and reports along with FMEA and hazard and risk list inputs needed for TRL 5 advancement NAR.

Table 4.7: PCS CTE-2 Component maturation path for turbo-machinery advancement to BrB fidelity (TRL 5).

Major Technology Milestones to TRL 5	#	**Timeframe (End Date)**	**Significance**
BrB Design Review	CTE2-4.1	Q1/Y3	SNP SME review of hardware development efforts for BrB-class PCS based on BB, M&S findings, and other available information.
Full scale (FS) PCS design complete with internal SNP review	CTE2-4.2	Q2/Y3	PSC hardware design complete and ready for fabrication.
Full scale PCS hardware fabrication complete – unit delivered and installed	CTE2-4.3	Q4/Y3	FS hardware fabricated with BrB-quality feedstocks and manufacturing methods - all components meeting alloy, purity, or other manufacturing specifications to allow for accurate assessment of PCS performance under realistic procurement and manufacturing scenarios. Hardware delivered and installed for testing in advance of test TRR. Hazards and risk lists reviewed and revised as necessary.

Table 4.7: PCS CTE-2 Component maturation path for turbo-machinery advancement to BrB fidelity (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
FS BrB CBC loop design and test requirements complete with internal SNP review.	CTE2-4.4	Q4/Y3	Design for CBC loop complete with "pre-2,500 hour test" shakedown requirements complete and reviewed by SNP SMEs. Ready for fabrication. Note: to include turbine, compressor, heat exchangers, etc.
BrB Heat Transfer Transients TRR	CTE2-4.5	Q4/Y3	Internal SNP review of transient testing plan complete including test objectives, selected facilities, test article design, testing conditions, and testing procedures. Ready for thermal transient testing.
BrB vibrations and loads evaluation TRR	CTE2-4.6	Q1/Y4	Facility and hardware inspection by SNP SMEs (and others if required) to assure test readiness. Thorough test plan review for vibration and loads complete (including test objectives, selected facilities, test article design, testing conditions, and testing procedures). Ready for vibe and load testing.
PCS heat transfer transients testing complete	CTE2-4.7	Q1/Y4	BrB testing and model comparisons to ensure delivered hardware capabilities sufficient for anticipated transient and off-nominal conditions in 2,500 hour test. Tests to assess operating transients and excursions (CTE-1-CTE-2 interface), electrical load changes (CTE-2-CTE-3 interface), and heat rejection system transients (CTE-2-CTE-5 interface).
Component level vibrations and loads testing (launch loads) complete with internal SNP review.	CTE2-4.8	Q1/Y4	Preliminary test completed to confirm that components can withstand launch loads and expected vibration environments and that further testing can proceed.
PCS heat transfer transient test review complete (TCR & MVR)	CTE2-4.9	Q1/Y4	Post-test evaluation of heat transfer transient test results with model comparison for model validation with recommendations for future model improvements. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues.
FS CBC loop structural and flow testing complete.	CTE2-4.10	Q1/Y4	Shakedown testing complete – ready to proceed to full 2,500 hour test.

Table 4.7: PCS CTE-2 Component maturation path for turbo-machinery advancement to BrB fidelity (TRL 5).

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
2500-hour BrB Non-Nuclear PCS TRR	CTE2-4.11	Q1/Y4	Internal SNP review of 2500-hour test plan including test objectives, selected facilities, test article design, testing conditions, and testing procedures. ATP to proceed to 2,500 test.
BrB Non-Nuclear PCS test complete - post-test review (TCR & MVR) complete	CTE2-4.12	Q3/Y4	Post-test evaluation of FS PCS test results with model comparison for model validation with recommendations for future improvements. Update FMEA analyses to include the results of testing and confirm there are no unresolved issues. This review will include the results of both post-test hardware inspection and modeling projections for lifetime (25,000 hour goal).
TRL/AD^2 Advancement NAR	CTE2-4.13	Q4/Y4	Non-advocate review to demonstrate that CTE-2 BrB testing and modeling efforts have met all goals specified for advancement to TRL 5.
Final IDD, FMEA, and Risk & Hazards Lists Completed	CTE2-4.14	Q4/Y4	IDD revised as necessary based upon BrB development. Revisions to FMEA and risk & hazards lists complete and delivered to SNP.

4.5 CTE-2 Technology Advancement Risks

The SNP project has performed a preliminary development risk assessment of the Brayton system with the support of non-advocate SMEs. This assessment is the start of a formal FMEA, the results of which will be documented as part of the overall PCS technology development efforts discussed in the previous section informing and guiding the component and subsystem development and testing.

An initial list of He-Xe closed Brayton cycle technology maturation challenges/risks associated with the NEP application are (in no particular order):

- High shaft speeds limit generator size and type
- Working fluid and thermal management issues at high-power
- Generator temperatures limited to below 500 K unless a higher control complexity, high temperature switched-reluctance generator is developed
- Seal life and functional challenges under launch loads, while subjected to launch and operational vibrational environments, and during various in-space maneuvers

- Bearing life and support challenges under launch loads, while subjected to launch and operational vibrational environments, and during various in-space maneuvers
- Minimization of overall system mass and reduction of compatibility between rotor and generator shaft speeds
- Turbine and pressure vessel material creep and potential corrosion.
- Required electromagnetic interference and radiation tolerance for controls
- Fabrication of a complex-geometry recuperator construction that has many bends and commensurate stress and pinch points
- Potential option for installation/operation of multiple generators on a single PCS shaft to electrically isolate thrusters
- Effect of the power system architecture, fault protection scheme, and response times (which differ for permanent magnet vs. switched reluctance alternator architectures) on the PCS design
- The potential freezing of the working fluid
- 1400 K design option may require the use of new and novel design approaches and associated new materials and manufacturing techniques

Table 4.8 and Figure 4.12 show an example of the ‘Top 5’ technical risks identified at this point by SNP SMEs. All risks will be fully described and tracked using risk assessments based upon NASA’s standard risk scale for consequence and likelihood as taken from GPR 7120.4D, *Risk Management Reporting.*

Table 4.8: 'Top 5' PCS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment** L	C	T	**Mitigation Strategies**
PCS-1	Material Selection	Materials for high temperature exposure/high pressure stress/potential chemical compatibility (turbinecompressor components, bearings, flow channels, heat exchangers) may require technology development	T	3	3	9	Develop a materials test and evaluation process and initiate specific materials and manufacturing process research and development on most likely power conversion system candidate materials/start task at authority to proceed (ATP)
PCS-2	Working Fluid	Fluid must enable high efficiency power generation and heat rejection at as high a temperature as possible to reduce radiator size. Must quantify He-Xe mixture properties at specified temperatures/target mole ratios & pressures including the potential for discharges at high voltage.	T	2	3	6	Detailed analytical assessment of He-Xe concentration options conducted in FY'22. Coordinate presentation of assessments and develop paths for maturation/refinement of analyses at the initial SME workshop
PCS-3	Bearings and Seals	Excess leakage or insufficient stiffness will degrade performance of the power convertor	T	3	2	6	Initiate design and mitigation tasks early in the project. Aim for early infusion of concepts into test beds and breadboard/brassboard-fidelity demonstrations

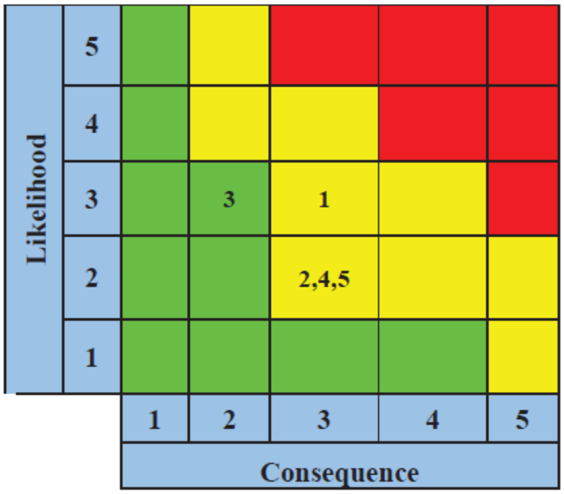
Table 4.8: 'Top 5' PCS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PCS-4	Transient Startup	Phase change, dynamic nonlinearities, system stability and controllability	T	2	3	6	Establishment of a power conversion testbed where Brayton power units in this temperature range and power class can operate with simulated reactor heat input, simulated radiator heat removal, and simulated electrical power extraction/start task at ATP + 1 year
PCS-5	Life Assessment	Uncertainty in data on material creep, corrosion, and erosion limits confidence in the system	T	2	3	6	Development of a material properties database and system models to permit design evaluations based on technology development demonstration activities (up to 2,500 hours), with results of trades and funded assessments used to refine the models / start task at ATP

4.6 PCS Maturation Summary

From an integrated system perspective, Brayton power conversion technology has significant advantages over competing technologies. Major advantages include:

- The ability to test at space-like vacuum levels in relatively modest, existing ground test facilities.
- High power density power conversion units that translate to system simplicity, low α, and an ability to more readily permit redundancy strategies.
- Availability of Brayton components based on extensive terrestrial applications.



Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩 3	🟨 1	🟨	🟥
2	🟩	🟩	🟨 2,4,5	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5
	Consequence				

Figure 4.12: PCS “Top 5” Risk Ranking Likelihood and Consequence Span.

- Demonstrated launch vibration and shock survivability/compatibility through various aircraft turbine and space cryocooler applications.

The major hurdles that must be addressed prior to use in a high-power NEP mission design are associated with the required endurance capability of the PCS at the required power levels and inlet temperatures. In this consideration, both the rotating-components in the Brayton engine and the heat-exchanger (especially the recuperator) must be proven for a long duration operation. Promising technology advancements have been achieved over the last decade in terrestrial applications and implementing and validating these technology advancements for space are at the heart of the PCS technology maturation plan. Clear milestones, documented risks and risk mitigation strategies, and NAR oversight are all specified in the maturation plan. As written, this four-year plan will use significant hardware development and testing efforts coupled with modeling and simulation activities and FMEA evaluations to determine the efficacy of Brayton power conversion systems for high-power NEP missions.

Chapter 5

Advancement Plan – CTE-3: Power Management and Distribution (PMAD)

A high-power (MW$_e$-class) NEP system requires a PMAD subsystem, here referred to as Critical Technology Element 3 (CTE-3), to couple with and generate electrical power from the PCS (CTE- 2) and transmit generated power to the electric propulsion subsystem (EPS) (CTE-4). This subsystem must also provide power to support operation of the spacecraft (non-electric propulsion) subsystems and to charge battery energy storage systems (BESS) as needed. The mass model used for analysis of this CTE includes not only the major power generation and transfer hardware (i.e., the generators, main switches, output transformers, transmission lines, and associated hardware), but also the switches and transformers required to support pumps located in CTE-5, a transformer to supply electricity to the spacecraft battery assembly (but not the battery assembly itself), and (if required) a generator starter assembly (i.e., inverter and associated components). The PMAD subsystem must also be able to reroute and dissipate excess power through a shunt radiator when CTE-2 is operating but CTE-4 is not (under both nominal and off-nominal conditions). Systems analyses indicate that an effective NEP configuration for a human Mars mission will require between 2 and 4 MW$_e$ (refs. [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 65, 104]) and SNP has chosen to focus on a 1 MW$_e$ building block approach for technology maturation and advancement. Figure 5.1 shows a generalized diagram for an NEP PMAD subsystem.

As shown in the figure, the major assemblies (MAs) are the generators at the CTE-2/CTE-3 interface, the switching network, and the transformers at the CTE-3/CTE-4 interface. The transmission lines (cables and connectors) are also key to the operation of the subsystem and contribute a non-negligible amount to the mass because of the very high-power levels being transmitted between CTE-2 and CTE-4. It is noted that the block diagram is highly generalized. For example, the positioning of the switching network with respect to the transformer(s) could change as the subsystem design is matured, but in all cases the switches will have to shunt power to alternate loads regardless of their positioning. The mass of the transformer secondary winding and the overall transformer efficiency will depend on the CTE-4 interface requirements. Under nominal conditions with the thrusters operating, approximately 90% of the power produced by CTE-2 will be transmitted to CTE-

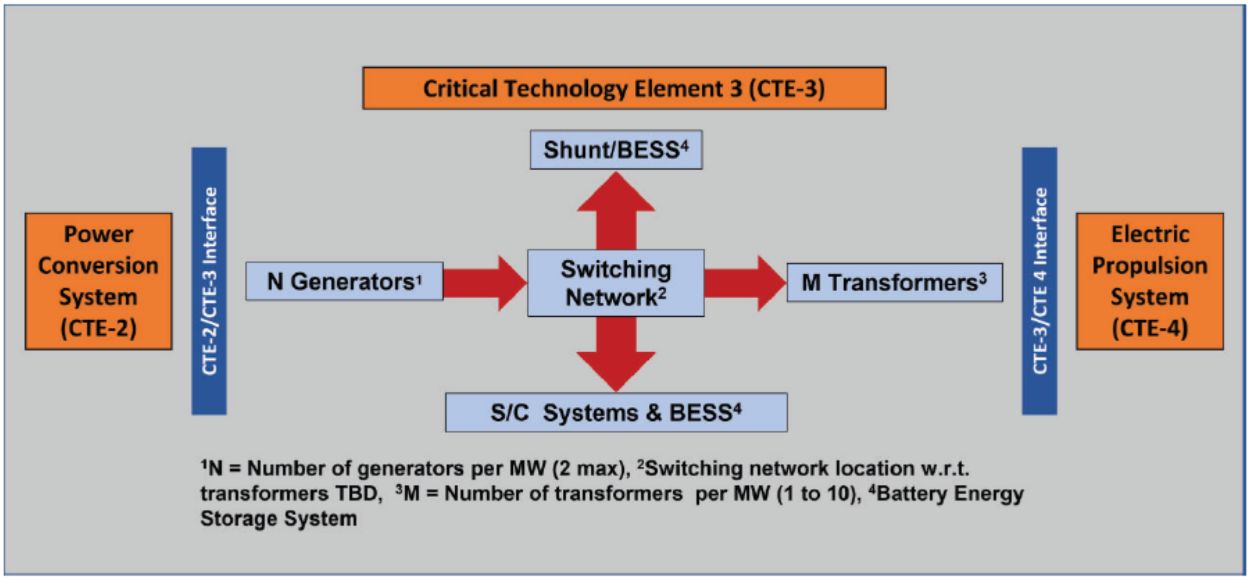


Figure 5.1: Generalized NEP PMAD subsystem showing major assemblies.

4. The bulk of the required technology development efforts will be focused on the generator, switching network, and the transformers required to condition power to the levels required at the CTE-3/CTE-4 interface.

In keeping with the robust SE&I philosophy described in the Introduction, a detailed Interface Description Document (IDD) will be developed for both major external interfaces (i.e., the CTE- 2/CTE-3 and CTE-3/CTE-4 interfaces). Preliminary discussions of these interfaces are provided below. The initial IDD's will be developed by SNP's CTE-3 lead after discussion at the opening workshop. These will be reviewed by SNP, circulated for SME evaluation if required, and then finalized, with the controlled version maintained by the SNP SE&I lead. The documents will be reviewed and revised as needed at each major relevant milestone, including as part of the NARs planned for technology advancement verification. In addition, IDD's will be generated for each MA-to-MA interface to ensure compatibility as PMAD breadboard and brassboard development progresses. These IDDs will be kept by the CTE-3 lead and reviewed by the SNP SE&I lead and/or SMEs as needed. It is noted that all applicable standards, including those required for human rating, will be identified at the opening workshop and applied if appropriate so the brassboard hardware developed to achieve TRL 5 will translate to TRL 6/prototype/flight-like designs without requiring appreciable additional research and maturation. For example, applicable requirements from NASA's SMC-S-010 "Technical Requirements for Electronic Parts, Materials, and Processes used in Spacecraft" will be used to identify the key features of all electronic component (e.g., switches) and material (e.g., generator and transformer components) technologies needed to make these technologies either directly applicable or easily evolvable to flight-quality hardware via standard engineering practices. NAR validation of this extensibility will also be a condition for technology advancement. Additionally, at the TRL 4 and TRL 5 non-advocate reviews, the latest CTE-3 technology status will be combined with the latest results from the development of all the other CTEs and incorporated into an evolving conceptual vehicle configuration assessment to ensure that the combined CTEs will lead to a feasible and practical vehicle configuration.

To meet the SNP ground rule to develop MW$_e$-class building blocks, both parallel-ganged 500 kW$_e$-capable strings and single 1 MW$_e$-capable string architectures will be considered at the start of the process for achievement to TRL 4. For the purposes of the development of this TMP, it is assumed that the PMAD output is independent of the thruster technology selection with the exception of the magnitude of the voltage (Vac) provided at the CTE-4 interface. That is, 1 MW$_e$ of transformer isolated output capacity will be provided at the CTE-3/CTE-4 interface at the frequency output by the generator (nominally 1.2 kHz – see Table 5.1) but at V$_{ac}$ stepped down from the output of the generator (nominally 1 kV – again, see below) to a voltage optimal for high-voltage input thruster (e.g., $\sim$600 V$_{ac}$ for a Hall thruster) or a low-voltage input thruster ($\sim$100 V$_{ac}$ for an MPD thruster). Rectification, isolation, and other control functions for the electric propulsion system will be on the CTE-4 side of the interface. This PMAD-specific ground rule was established to assure that the interface is clearly described and all EP system-specific functionalities are addressed within the development of CTE-4. Using this approach ensures that the full system implications of the EP system choice are accounted for within CTE-4. As the technology maturation process is executed, the CTE-3 and CTE-4 teams will occasionally revisit the CTE-3/CTE-4 interface boundary to determine if its location should be shifted.

Table 5.1: KPP Guidance for CTE-3 Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Power per Generator ($\mathrm{MW_e}$)	0.5	1.0	1 $\mathrm{MW_e}$ "building blocks" are key to overall technology maturation strategy – decision on number of units per $\mathrm{MW_e}$ is a research and development Milestone
Generator Output	∼1 kV / 2 kHz		SME-generated preliminary AC voltage characteristics subject to early project trade studies
CTE-3 α ($\mathrm{kg/kW_e}$)	4	3	Threshold and target α values derived from mission analysis and SME technical inputs
Subsystem Efficiency (η in %)	93	95	Threshold and target η values derived from mission analysis and SME technical inputs
Lifetime (Years)	3	10	3 years provides margin for single (2.5 year) human mission to Mars, 10 years enables multi-trip reuse
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for electronic equipment.

Other components, subassemblies, and assemblies will be required to provide full functionality for the eventual spacecraft PMAD subsystem. These include, for example, the high temperature 750+ K radiator required to shunt power when the propulsion system is not running; connectors, isolators, and power harnesses necessary for electrical power transmission; the separate components and subassemblies required to provide power to the spacecraft; and the low temperature radiators required to maintain the PMAD components (generator, switching network, transformers, etc.) at acceptable temperatures (∼300 K). The development of these technologies, while challenging, is considered straightforward engineering and will be discussed only briefly here and pursued in the implementation phase only to the extent necessary to provide credible TRL 4 and TRL 5 demonstrations. For example, the shunt radiator temperature and placement will be critical to system operation, but the assembly will likely be some type of carbon-based resistors with fins capable of operating in the 750–1000 K range. Designs for cross-strapping, controls, sensors, etc., will be developed to the extent necessary to assure that the three major PMAD assemblies will be at a maturity level capable of supporting an integrated spacecraft design. SNP CTE technology maturation efforts will focus on:

1. A $\mathrm{MW_e}$-class generator that transforms rotational motion from a Brayton power converter into AC electrical power with a detailed IDD for the CTE-2 to CTE-3 interface,
2. A switching network capable of rapidly switching from the CTE-4 interface to the shunt resistor/radiator,
3. Transformer technology to provide the required output at the CTE-3/CTE-4 interface with a detailed IDD for the interface,
4. The integration of these three MAs into the overall CTE-3 subsystem with demonstrations of both the endurance necessary to project sufficient life and the stability necessary for performance under expected transient conditions,
5. CTE-3 focused M&S efforts required to maximize confidence in the projections of lifetime and performance, and
6. Comprehensive FMEA and individual hazard analyses including a worst-case assessment for CTE-3.

The WBS developed for SNP management of the PMAD development effort is shown in Figure 5.2.

Both exogenous hazards to the spacecraft and physical hazards in development testing will be considered. A preliminary list of these will be generated by SNP SMEs and refined as the development efforts progress. Necessary activities to mitigate exogenous hazards will be included under the appropriate technology development efforts shown in the WBS. For example, technology development to mitigate the impacts of cosmic radiation on the soft magnetic materials for transformers would be implemented under the “Core” box in the transformer column. Safety hazards such as the inherent danger of machinery rotating at ∼30 krpm, high voltage breakdown, and anomalous high energy transformer events will be addressed using through project-managed Safety and Mission Assurance processes.

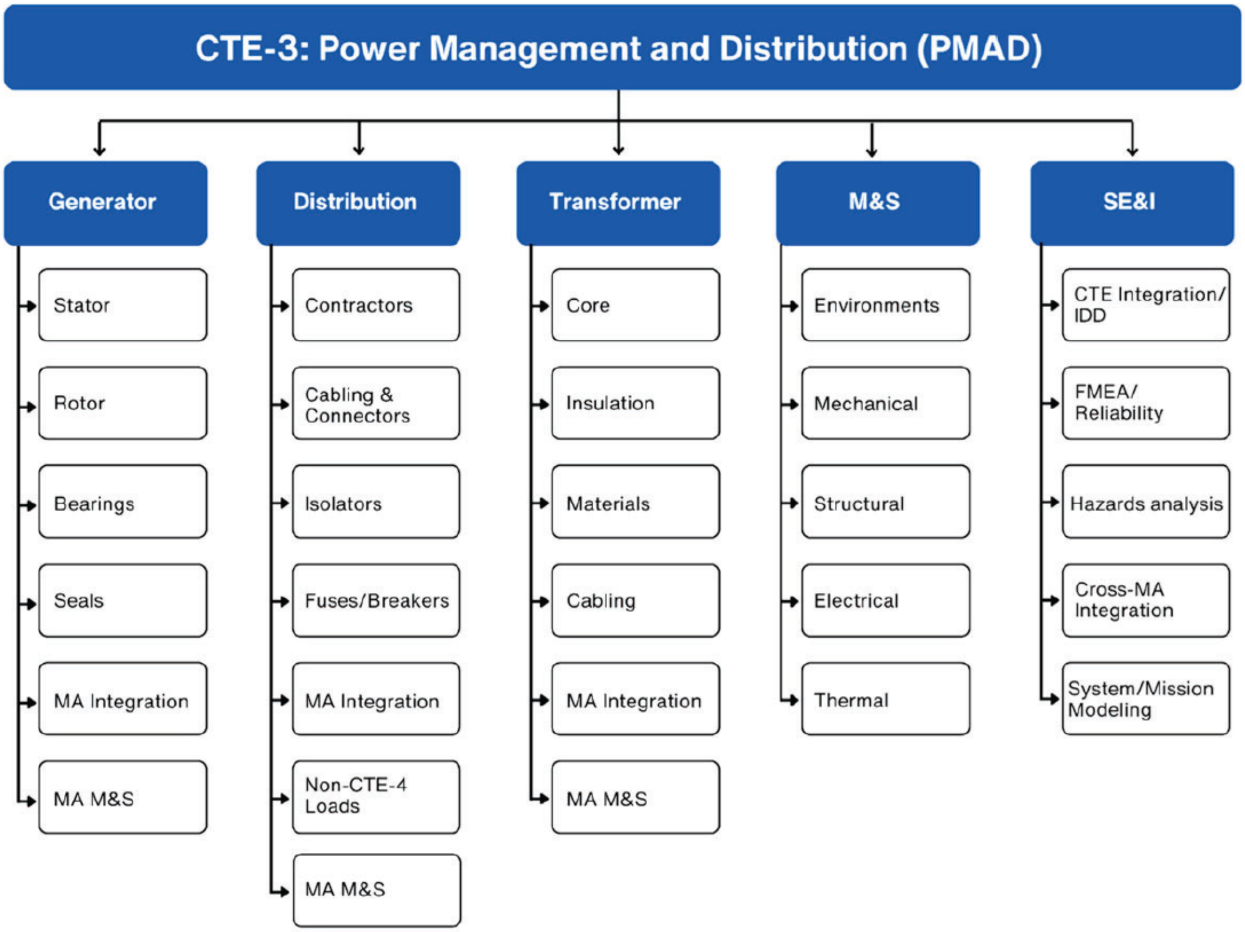


Figure 5.2: WBS for PMAD subsystem development management.

Based on the outputs of the SNP-sponsored CTE-focused Technology Interchange Meetings (TIMs) (ref. [30]), ongoing SNP-sponsored systems analyses, literature research, and internal and external SME discussions, the scope of the required CTE-3 development effort has been narrowed through the selection of preliminary KPPs based on the use of a Brayton cycle-based power conversion technology for CTE-2. SME inputs, nominal generator output values of 1 kV_{ac} and 2 kHz have been chosen as the starting point for trade studies aimed at optimizing these values with respect to subsystem specific mass, transmission line losses, isolation requirements, and projected redundancy requirements. For these trade studies, the generator output can be between 500 kW_e (two units ganged for the 1 MW_e building block) and a single 1 MW_e-capable generator. The voltage and frequency values will be revisited as technology advancement efforts proceed. Similarly, SME assessments to date indicate that a permanent magnet-based rotor affixed directly to the Brayton shaft external to the turbine is the most likely technology choice for the generator, but alternate approaches like wound rotors or hybrid devices (ref. [41]) would be considered if a compelling technical case is made by an offeror. Table 5.1 lists the preliminary KPPs for CTE-3. The plan and KPPs are evolutionary and, as project technology advancement efforts progress, these may be modified based on the results of technical advancement, SNP engineering analysis, outputs from

NARs, and evolving requirements at the CTE-2 and CTE-4 interfaces (mechanical, thermal, electrical, etc.).

5.1 PMAD Background, State-of-Art, and Technology Gaps

SNP has ground ruled that the CTE-3 interface with CTE-4 will be independent of the propulsion system selection with the exception of V_{ac} at the transformer output to ensure that there are no subsystem-to-subsystem gaps in the TMP and that the major masses and efficiencies driven by a given subsystem are managed within that subsystems technology maturation plan. This approach also enables the technology maturation activities for the different subsystems to proceed independently, with well-defined interfaces. Based on this and the requirement for 1 $\mathrm{MW_e}$ building blocks, the simplest high level PMAD block diagram is shown in Figure 5.3. The MAs in this configuration include a single 1 $\mathrm{MW_e}$ generator (G1), a central switching network capable of switching power at the 1 kW/2 kHz (nominal) generator output, and a single transformer to isolate the output and step down the voltage to the level required for the thruster of interest (e.g., Hall ∼600 V_{ac}, MPD ∼100 V_{ac} for MPD). There are multiple permutations for the PMAD in the context of both the development of technologies (e.g., 500 $\mathrm{kW_e}$ versus 1 $\mathrm{MW_e}$ generator, specific switch and transformer characteristics) and overall system optimization. The potential variations are based on the power level (resulting in a single string or ganged approach), the number of transformers selected, and the number and positioning of the switches.

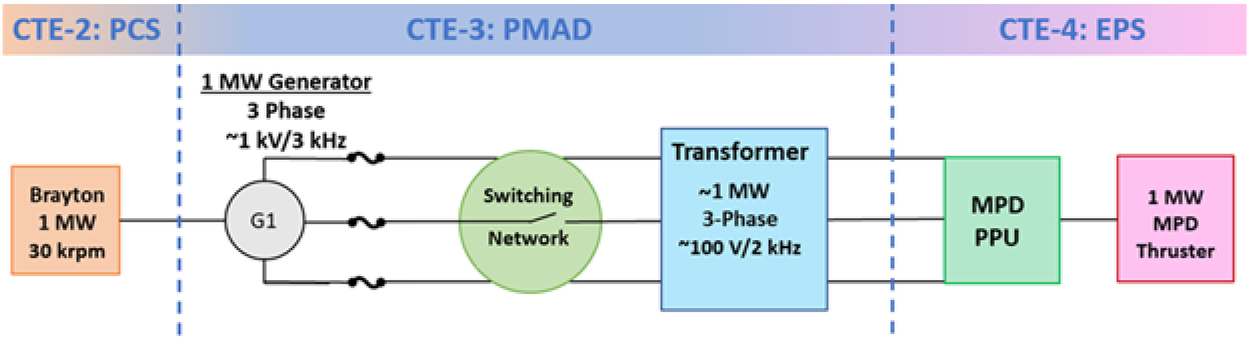


Figure 5.3: 1-$\mathrm{MW_e}$ PMAD design assuming a single 1-$\mathrm{MW_e}$ generator with a 1-$\mathrm{MW_e}$ thruster (single MPD shown).

Figure 5.4 shows a more complex configuration (chosen as the likely upper bound of PMAD complexity) with two parallel 500 $\mathrm{kW_e}$ generators driving ten individual transformers and switching networks. In this case, the EPS interface could consist of, for example, ten independent 100 $\mathrm{kW_e}$, ∼600 V_{ac} outputs to power ten separate Hall thruster DDUs (MTAS case) or ten independent 100 $\mathrm{kW_e}$, ∼100 V_{ac} PPU input modules with outputs ganged to power one MPDs (1 $\mathrm{MW_e}$ total). In both cases, the output frequency would be the same (a nominal starting point for the TMP of 2 kHz). In the diagrams, the switching network has been simplified. The circled switching network symbol represents all switches required (probably multiple switches per phase). to route the power either to the CTE-4 interface for normal thruster operation or to the shunt resistor/radiator in instances where the generator is operating but the thrusters are not operating.

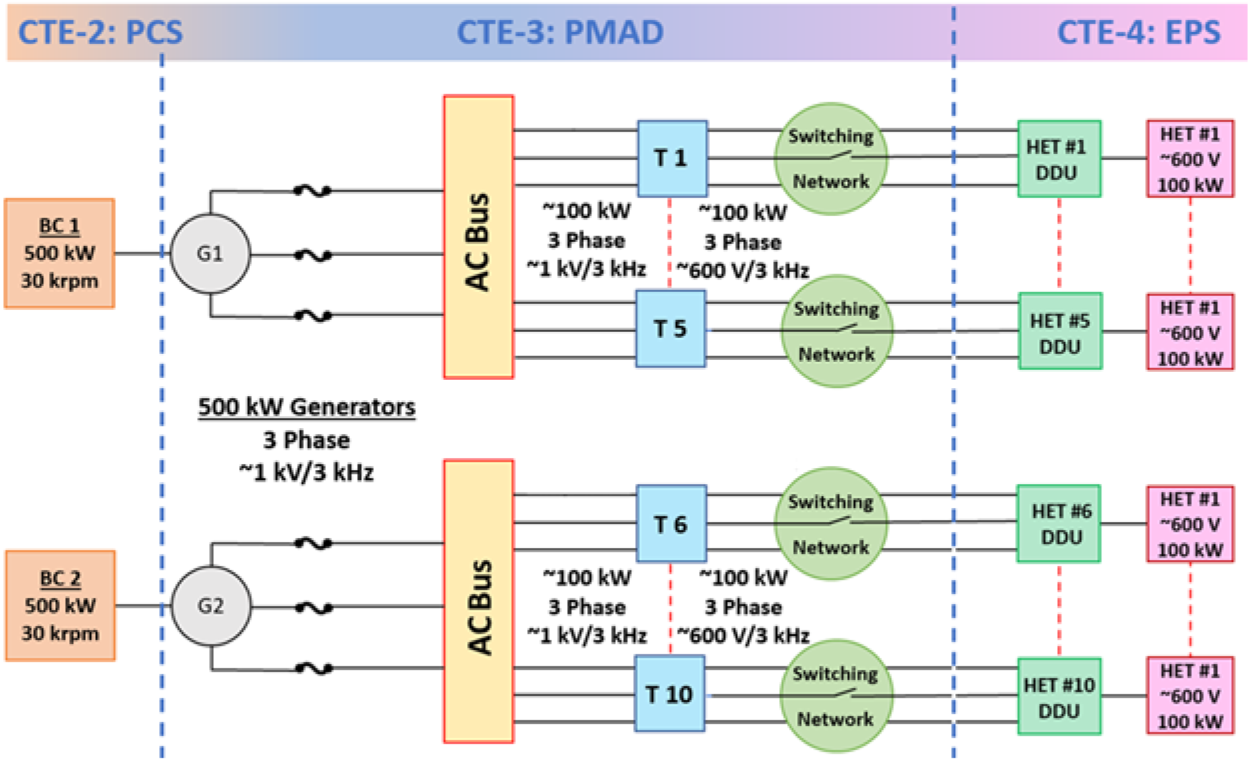


Figure 5.4: 1-MW$_e$ PMAD design supporting an EPS assuming multiple 500-kW$_e$ generators with multiple 100-kW$_e$ PPU/DDU-type inputs to Hall-effect thrusters.

Not shown, but also required, will be any added hardware to satisfy requirements on power conditioning, filtering, isolation, fault control, redundancy, and a number of other design factors for a high-power distribution system, including potentially combining multiple generator outputs and later distributing those outputs to a number of thrusters and other non-propulsive loads.

Table 5.2 shows the MAs, components, and other aspects of the PMAD subsystem with a brief description of the technical advancements needed prior to considering the technology for a flight application. The key technologies requiring focused research and development are the electrical generator, switching network, and transformer. These, along with the test facilities and technology-specific modeling needed to demonstrate integrated operation and project that the subsystem will meet the required lifetime represent the primary focus of this CTE-3 TMP.

Table 5.2: CTE-3 Major Technology Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Generator (Alternator)	Adaptation of existing MW_e-class alternator technology (stator, rotor, bearings, seals, & cooling capability) to provide a compact, low-mass assembly to convert Brayton-driven rotating shaft (∼30 krpm) to 3 phase AC power at ∼1 kV/2 kHz capable of a minimum of 3 years of operation in space without maintenance. Evaluation of potential for dual use as motor to start turbine using stored energy.
2	Switching Network	Adaptation of existing vacuum or solid-state switching technologies to the current/voltage/frequency requirements of a 1 MW_e-class NEP system with reliable operation in the space environment for a minimum of 3 years without maintenance.
3	Transformer	Development of low mass transformers to provide the 1 kV/2 kHz (nominal) output at the CTE-3/CTE-4 interface. Transformers to be capable of operation for a minimum of 3 years in space without maintenance.
4	Cable, harnessing, connectors & isolators	Adaptation of existing cable, harnessing, and electrical isolation technologies to provide the power transmission and isolation required in space environment (radiation, thermal) for the MW_e-class NEP application (25,000 hours minimum).
5	Heat Rejection	Development of cooling technologies and strategies for all PMAD components, subassemblies, and major assemblies (generator, switch, transformer, and other associated hardware (e.g., electronics)).
6	Energy Storage	Adaptation of existing Battery Energy Storage System (BESS) technology to provide buffering of alternator output against excess energy (in the event of thruster shutdown) and provide starting power for a turbine (if needed).
7	Controls	Adaptation of existing power monitoring and logic controls to operate in the space environment. Controls will manage startup and shutdown, fault sensing and recovery, switching commands, and system health monitoring performing data acquisition and real-time response, while interfacing with other vehicle systems as required.
8	Test facility	Development of a test facility that can test a MW_e-class PMAD system, including available AC power, vacuum facilities, cooling capabilities, and the ability to realistically emulate the interactions at interfaces with other CTEs.

Table 5.2: CTE-3 Major Technology Advancement Requirements.

	Technology Description	**Advancement Descriptions**
9	Subsystem Integration	Conduct a progressive fabrication/modeling/test program that results in the demonstration of a 1 MW_e BrB PMAD subsystem incorporating all 3 major assemblies (generator, switching network, transformers) for a minimum of 2,500 hours using realistic CTE-2 and CTE-4 interface emulators capable of demonstrating operation through planned and unanticipated transients.
10	Subsystem Modeling	Development of a modeling suite (dynamic electrical, thermal, mechanical, structural, environmental) and FMEA that credibly projects 25,000+ hours of operation when validated with data from 1 MW_e/2,500-hour testing and other available information.

There is presently little development aimed specifically at the advancement of MWe-class NEP PMAD capabilities. Both the recent NESC (ref. [28]) and NASEM (ref. [29]) reports indicate a low technology readiness for NEP-class PMAD. While the use of electric propulsion in space has seen rapid growth over this time (refs. [104, 105, 106]), the qualified SOA maximum power per thruster is below 10 kW_e and all subsystems to date have been operated using solar array-powered direct current (DC) PMAD technology. The International Space Station (ISS) PMAD system handles roughly 240 kW_e, but, like all other present flight systems, it too uses DC solar power generation (ref. [107]) and there are no electric propulsion systems on the ISS to demonstrate coupled higher-power PMAD-to-thruster operation. The planned Lunar Gateway PPE (ref. [108]) is designed to use solar arrays to produce 60 kW_e of DC power at a bus voltage in the 120-160 V range. The use of solar arrays producing DC power leaves little commonality with MW_e-class NEP applications. In the early 2000s, Project Prometheus focused on the development of a 100 to 200 kW_e-class NEP system for the JIMO mission (refs. [15, 16, 17]). During that program, a 100 kW_e-class AC generator emulator testbed (shown in Figure 5.5) was developed by Hamilton Sundstrand (ref. [17]).

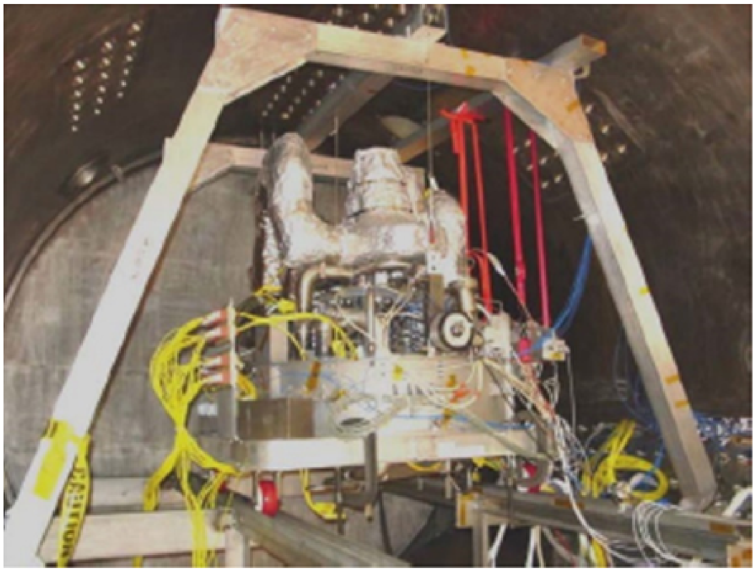


Figure 5.5: 100-kW$_e$-class emulator test-bed developed under Project Prometheus.

Specific technology issues such as bearings and seals to couple the Brayton power converter to the electrical generator assembly were also addressed to an extent under Project Prometheus (ref. [17]), but significant TRL/AD^2 hardware advancements were not achieved. While these efforts were conducted almost two decades ago, relevant lessons learned were retained and will be incorporated in the present effort. Close coordination with CTE-2 development of PCS bearings and seals will help eliminate redundant or duplicative efforts.

Analogs for all MAs exist in either (or both) the terrestrial power generation industry or NASA's electric aircraft (EA) program. While most of the EA work is company proprietary, multiple demonstrations of high-power EA generators are in progress (ref. [109]). These include MW$_e$-class Brayton-powered generators and a full flight demonstration using two 650 kW$_e$ generators supplied by magniX (ref. [110]). For terrestrial use, fission-based microreactor technology at power levels in the range of 1-20 MW$_e$ is being developed for both DoD and civilian applications (ref. [75]). Large commercial power plants employ steam-driven generators, switching systems, and transformers operating at power levels that are orders of magnitude larger than the present NEP TMP contemplates. Technologies from terrestrial applications and the EA program are, to some degree, relevant, but major differences related to requirements for low subsystem mass and operation in the space environment for a minimum of three years without maintenance exist and will drive advancement efforts. The following discussion describes the SOA for existing MA technologies and key gaps with respect to the NEP application. Much of the relevant information on commercial EA programs is company-proprietary, but non-proprietary inputs on differences between ongoing EA activities and the NEP requirements have been provided by SMEs with insight into both the EA efforts and NEP systems.

MA 1 – Generator (a.k.a. Alternator) SOA and Gaps: NASA has funded significant generator development work in conjunction with the BRU development program in the 1980s (refs. [111, 112, 113]). AiResearch was the primary hardware developer, focusing on the development of 10 kW$_e$ units capable of over 30,000 hours of endurance (ref. [114]). The

BRUs use He-Xe mixtures as the working fluid and included the generator as an integral part of the assembly. The shaft speeds were typically 36 krpm. For most tests, four-pole modified Rice/Lundell alternators were used to produce 2 to 10 kW_e of 1.2 kHz, 3-phase AC power (refs. [115, 116, 117]). Long-life bearings and electrical seals were developed and integrated into some of the tests (refs. [118, 119]). Though much of this research was performed five decades ago and at power levels two orders of magnitude below the NEP target, many of the lessons learned will still inform technical decisions at the outset of the present project. In the same timeframe, motor operation (for starting) was also pursued (ref. [120]) and SNP will evaluate the efficacy of including this capability into the PMAD system.

There are significant, potentially relevant development efforts in progress for “small” (1-10 MW_e) terrestrial systems and technologies from even larger systems may also be adaptable. Most terrestrial generator systems produce 3-phase AC power, operating in the 50/60 Hz range. Large $\geq$10 MW_e generators are typically steam driven with shaft speeds in the 3000 to 3600 rpm range. Common portable units ($\sim$10 MW_e) are driven by hydrocarbon-fueled reciprocating or gas turbine engines with shaft speeds between 900 and 1800 rpm. The larger 50/60 Hz systems employ wound field rotors for voltage control while smaller units typically employ permanent magnetbased rotors. The $\sim$30 krpm shaft speeds anticipated to optimize generator mass are estimated from past NEP system analyses (refs. [111, 112, 113, 116]) and are subject to additional analysis at program initiation – these generator shaft speeds are essentially an order of magnitude beyond the terrestrial experience base. Generators for aircraft auxiliary power units typically operate at 400 Hz with shaft speeds in the 7 to 12 krpm range for 10 kW_e at $\sim$30 V_{ac} range -– well below the levels required for a high-power NEP system.

Keeping the generator assembly within acceptable temperature limits is a major hurdle in generator development. Ground-based systems typically employ cooling that is not compatible with the space environment. Large terrestrial stators, for example, employ liquid cooling and interior components are typically cooled using a hydrogen fill (low “windage” drag/high thermal conductivity) with an external heat exchanger. Similarly, below the 2.5 MW_e range, cooling is often accomplished via a shaft mounted fan. Neither of these options are suited for use in space and SNP will be required to advance the generator cooling technology. In a similar vein, highpower stationary alternators typically use Babbitt-type bearings with oil film lubrication while common ball bearings can be used in low power devices. Neither of these alternatives translate well to the NEP application. The gas foil bearing technology from past development efforts (e.g., BRU, Prometheus) provide a quality starting point but this area is expected to require significant SNP focus to recapture and advance the state of the art.

The permanent-magnet-based rotor designs being developed in the EA program at power levels of $\sim$1 MW_e share some commonality with those contemplated for CTE-3 but significant differences exist due to the differences in operating environments. Major ongoing commercial developments (ref. [121]) are proprietary but key insights into potential synergistic developments will be available through NASA SMEs with direct knowledge of EA progress. The ongoing EA generator work is well-funded and moving forward rapidly. Figure 5.6, for example, shows an exploded conceptual view of a 200 kW_e “proof-of-concept” generator that was developed at the University of Wisconsin for The Ohio State University (ref. [122]). A follow-on full-scale (FS) 1 MW_e unit is scheduled for near-term fabrication and testing in the NASA Electric Aircraft Test (NEAT) Facility (ref. [123]). Switched reluctance generator technology under development for automotive, wind energy, EA, and other applications (ref. [124, 125, 126, 127, 128, 129, 130]) may offer advantages for the high-power NEP generator application.

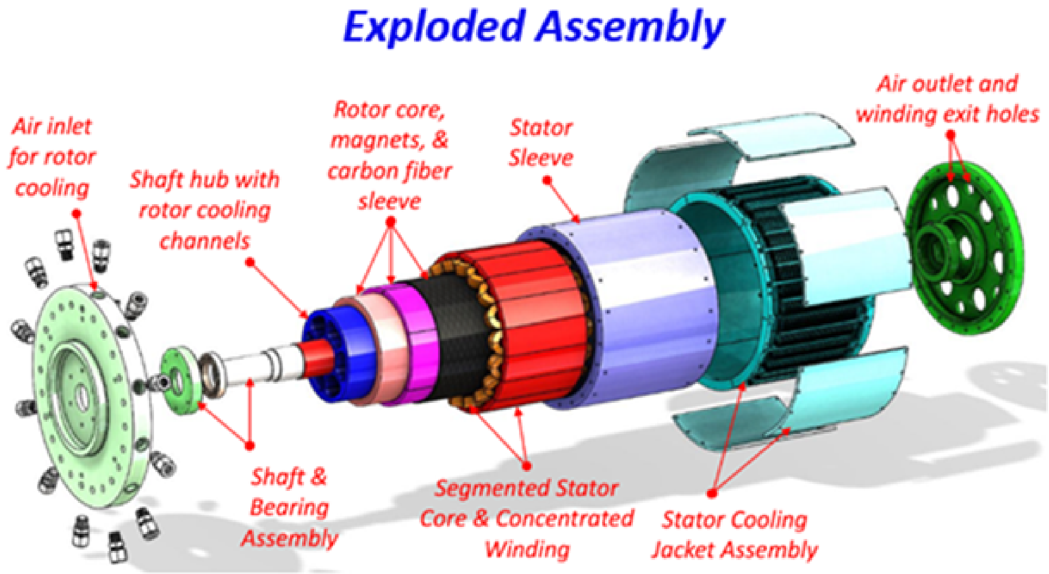


Figure 5.6: Conceptual View of the 200 kW$_e$-class Electric Generator Being Developed at The Ohio State University Under NASA EA Program Funding (ref. [126]).

While the 1980s BRU and ongoing terrestrial and EA generator efforts provide a rich background of available technologies, there are also major differences between these systems and a humanrated MW$_e$-class NEP space system. These areas of difference form the basis for the gaps shown in Table 5.3 that must be addressed in the planned SNP technology advancement program.

Table 5.3: Major Generator Technology Gaps and Advancement Requirements.

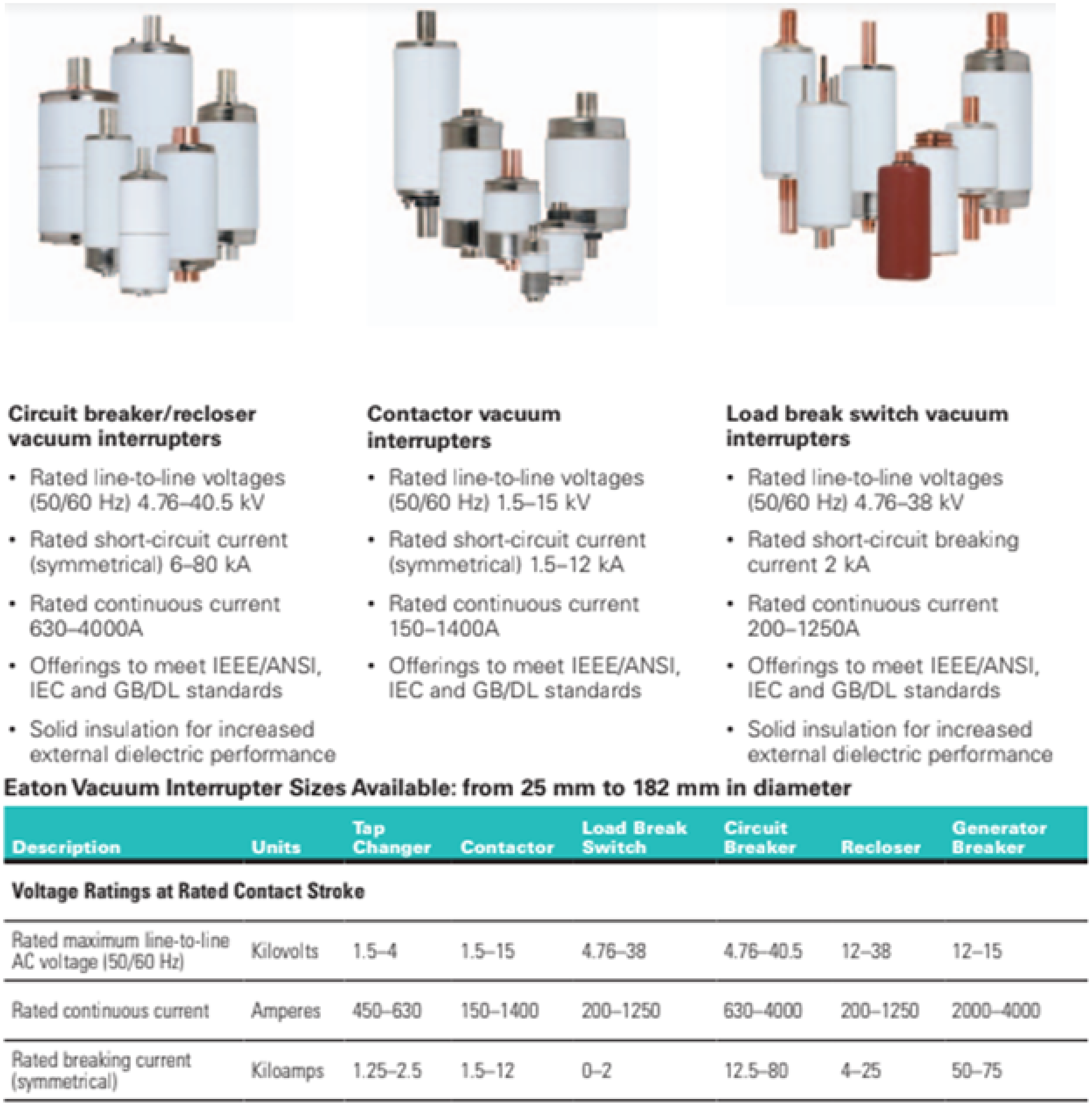
	Technology Description	**Advancement Descriptions**
1	Bearings	Terrestrial & aeronautical (EA) designs employ oil bearings. An NEP system will require low-leakage bearings. Work from the BRU and Prometheus programs provides directions but must be revisited and assessed for scaling to power levels of an order of magnitude or more.

Table 5.3: Major Generator Technology Gaps and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
2	Thermal Management	Standard shaft-based fans and oil cooling schemes will be replaced by advanced cooling schemes (e.g., He-Xe flow coupled from the Brayton working fluid, pulse-tube cryocooling). Radiation-cooling may suffice for the stator exterior, but both this and the use of dielectric fluid cooling require evaluation.
3	Seals	Labyrinth sealing technology will replace conventional lubricated technology for moving mechanical components. Hermetic sealing is required for electrical feedthroughs. Work from the BRU and Prometheus programs (if applicable) must be revisited and assessed for scaling to power levels of an order of magnitude or more.
4	Gearbox	Conventional systems typically employ a gearbox between the Brayton rotating shaft and the generator. SME inputs recommend not using a gearbox in the NEP application rather, the development of an assembly which matches the rotational speed of the Brayton shaft to the desired generator output frequency was recommended.
5	Radiation Hardening	Radiation (sourced from the reactor and incident from the deep space background) is well-beyond those encountered in conventional applications and shielding requirements will have to be developed and met.
6	Cold Soak	The space environment will require materials that can endure cold soaks, including cold start considerations more extreme than those for terrestrial applications.
7	Rotordynamics	Requirement for a low mass, sealed vessel containing a 30 krpm rotor shaft-based generator creates requirements for analysis of operational modes that can be destructive. These modes may not be present in conventional systems operating at much lower rotational speeds or transmitting shaft power through a gearbox.

MA 2 – Switching Network (a.k.a. Switches, Switchgear) SOA & Gaps: The major issue with distribution is the development of switching technologies for use in a high-power NEP system. As discussed previously, existing switch/contactor technology may be readily adaptable to NEP requirements and an evaluation of adaptability will be conducted at the outset of the project. Other technologies such as harnessing (including cabling and connectors) are deemed to be straightforward engineering that are, to some extent, being addressed elsewhere. For example, ARPA-E is currently investing ∼\$10M in the Connecting Aviation By Lighter Electrical Systems (CABLES) program focused on low mass, high altitude-capable electrical systems (ref. [131]). SNP has SME insight into these programs and will evaluate NEP technology advancements that can be derived from this work, but there are other potential issues (e.g., effects of radiation from a reactor and from the natural deep space radiation environment on key components) that must be addressed directly by SNP. A 'battleship' test apparatus approach to connection requirements will be employed for advancement to at least TRL 4, with a determination prior to the planned TRL 4 NAR of any focused research and development required for TRL 5 advancement.

For switching, the SOA consists of mechanical vacuum contactors (switches) that are used in the terrestrial power industry. These devices employ mechanical contacts, are available in the voltage/current ranges anticipated for use in MW_e-class systems, and are designed for operation without maintenance for many more hours/cycles than anticipated during a three-year Mars transit. They can be commanded either directly or remotely (analogous to space operation, commanded through either an onboard controller/flight computer or by external ground commands). Multiple vendors exist and typically offer families of products like the ones shown in Figure 5.7 (ref. [132]). Additionally, a significant advancement in potentially relevant very high-power (420 kV/63 kA) circuit breaker technology was recently unveiled by General Electric's Renewable Energy Grid Solutions group (ref. [133]). Finally, recent advances in gallium nitride (GaN) wide band gap (WBG) switching technology may be applicable depending on the switch position and current/voltage requirements in the final PMAD configuration (ref. [134, 135]). For example, 200 V/90 A switches are currently available and no known physical barriers exist to increasing either the switch voltage or current capabilities (ref. [136]). An SME-led review will be held at the outset of the maturation effort to more closely evaluate off-the-shelf technology and to ensure no rapidly evolving research and development efforts are overlooked.



Circuit breaker/recloser vacuum interrupters

- Rated line-to-line voltages (50/60 Hz) 4.76–40.5 kV
- Rated short-circuit current (symmetrical) 6–80 kA
- Rated continuous current 630–4000A
- Offerings to meet IEEE/ANSI, IEC and GB/DL standards
- Solid insulation for increased external dielectric performance

Contactor vacuum interrupters

- Rated line-to-line voltages (50/60 Hz) 1.5–15 kV
- Rated short-circuit current (symmetrical) 1.5–12 kA
- Rated continuous current 150–1400A
- Offerings to meet IEEE/ANSI, IEC and GB/DL standards

Load break switch vacuum interrupters

- Rated line-to-line voltages (50/60 Hz) 4.76–38 kV
- Rated short-circuit breaking current 2 kA
- Rated continuous current 200–1250A
- Offerings to meet IEEE/ANSI, IEC and GB/DL standards
- Solid insulation for increased external dielectric performance

Eaton Vacuum Interrupter Sizes Available: from 25 mm to 182 mm in diameter

Description	Units	Tap Changer	Contactor	Load Break Switch	Circuit Breaker	Recloser	Generator Breaker
Voltage Ratings at Rated Contact Stroke							
Rated maximum line-to-line AC voltage (50/60 Hz)	Kilovolts	1.5–4	1.5–15	4.76–38	4.76–40.5	12–38	12–15
Rated continuous current	Amperes	450–630	150–1400	200–1250	630–4000	200–1250	2000–4000
Rated breaking current (symmetrical)	Kiloamps	1.25–2.5	1.5–12	0–2	12.5–80	4–25	50–75

Figure 5.7: Example of a family of available commercial vacuum switching products (Eaton Industries).

PMAD technology gaps and required advancements are shown in Table 5.4. It is noted that the PMAD advancement plan currently shows advancements from the current SOA through TRL 4/AD^2 3 to an ending point of TRL 5. While further planned evaluation of existing switch technology may show a direct path to TRL 5, SNP assumes an intermediate advancement through TRL 4.

Table 5.4: Major Switching Network Technology Gaps and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Current and Voltage Ratings	Specified ranges for the differing devices encompass the anticipated requirements - after final device-type selection, design tailoring for NEP-specific ranges may be necessary.
2	Radiation Hardening	Terrestrial devices are not qualified for the exposure to anticipated deep space or reactor radiation environments. This may require redesign and/or the addition of shielding.
3	Packaging	Thermal and mechanical environments and loads (e.g., shock, vibe) between ground and space applications will be significantly different. SOA materials and structures will potentially require evaluation and modification.
4	Frequency Capability / Response Time	SOA technology has been developed for 50/60 Hz systems. While preliminary SME analyses suggest that operation at ∼2 kHz should not be an issue, in depth evaluation and demonstration will be required. The response times associated with SOA switches appear to be compatible with NEP PMAD requirements.
5	Reliability	SOA devices typically have lifetimes and cycling ratings beyond those required for NEP. Because in-mission replacement is not possible for NEP, reliability will need to be quantified and reviewed with modifications implemented and testing performed as necessary to validate operation.

It is noted that solid-state switches are a potential option, but a major potential issue for solid-state devices is radiation hardening. Solid state technology will be further evaluated in the early stages of TMP execution and development will be supported as a risk mitigation option if SME assessments show this to be warranted.

MA 3 – Transformers SOA & Gaps: For the high-power NEP application, specific thruster power levels or input characteristics have not been selected. For practical purposes, however, they are bounded at the low end by HETs operating at a minimum of 100 $\mathrm{kW_e}$ (with a cluster of 10 yielding a 1 $\mathrm{MW_e}$ system) and at the high end by a single 1 $\mathrm{MW_e}$ MPD thruster. The voltage supply requirements for these two thruster options are different (as stated previously in this section and in the following section on CTE-4), resulting in different secondary winding masses and thermal losses for each transformer option. System trades to determine the number of required transformers will depend on multiple factors such as mass minimization and thruster string design, where each string could include multiple transformers (one for the input of each Hall thruster DDU or one for each of the multiple ganged power conversion modules of an MPD PPU) or as little as a single transformer with multiple taps to feed, for example, an entire MPD PPU. The specialized nature of spaceflight will require significant transformer research and development including, for example, exposure testing to demonstrate required radiation tolerance for soft magnetic materials. For cost effectiveness, most terrestrial applications (where mass is not a major consideration) employ transformers that contain conventional silicon steel (Fe-Si) cores. These are oil-filled and typically rely on natural convection for cooling. At a given power rating, transformer mass is inversely proportional to frequency. Ferrite-core transformers have been used when mass or volume becomes an issue or when the operational frequencies produce excessive losses in Fe-Si transformer cores. NASA sponsored significant research and development on low mass power magnetics for aerospace applications in the 1980s under the power magnetics technology program at GRC (then the Lewis Research Center) (ref. [137, 138]). Major areas of research were mass optimization and thermal control. Significant reductions in mass were realized up to the 20-50 kHz range (well beyond the range envisioned for NEP). Both conduction and HP cooled devices were evaluated up to ∼25 kVA (with projections to higher power) for applications ranging from traveling-wave tubes to electric propulsion. GRC's Materials Division currently supports significant research on advanced magnetic materials and has established a world-class advanced magnetics development laboratory (ref. [139]) (see Figure 5.8) that can provide SNP with design and prototyping capabilities for rapid iteration on the transformer design during the early stages of the advancement effort.

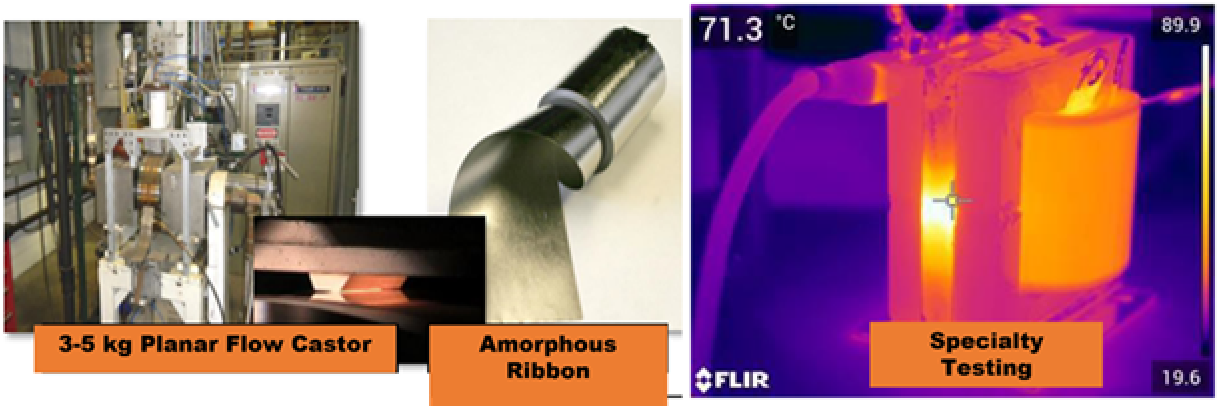


Figure 5.8: Examples of Capabilities at the GRC Advanced Magnetics Laboratory.

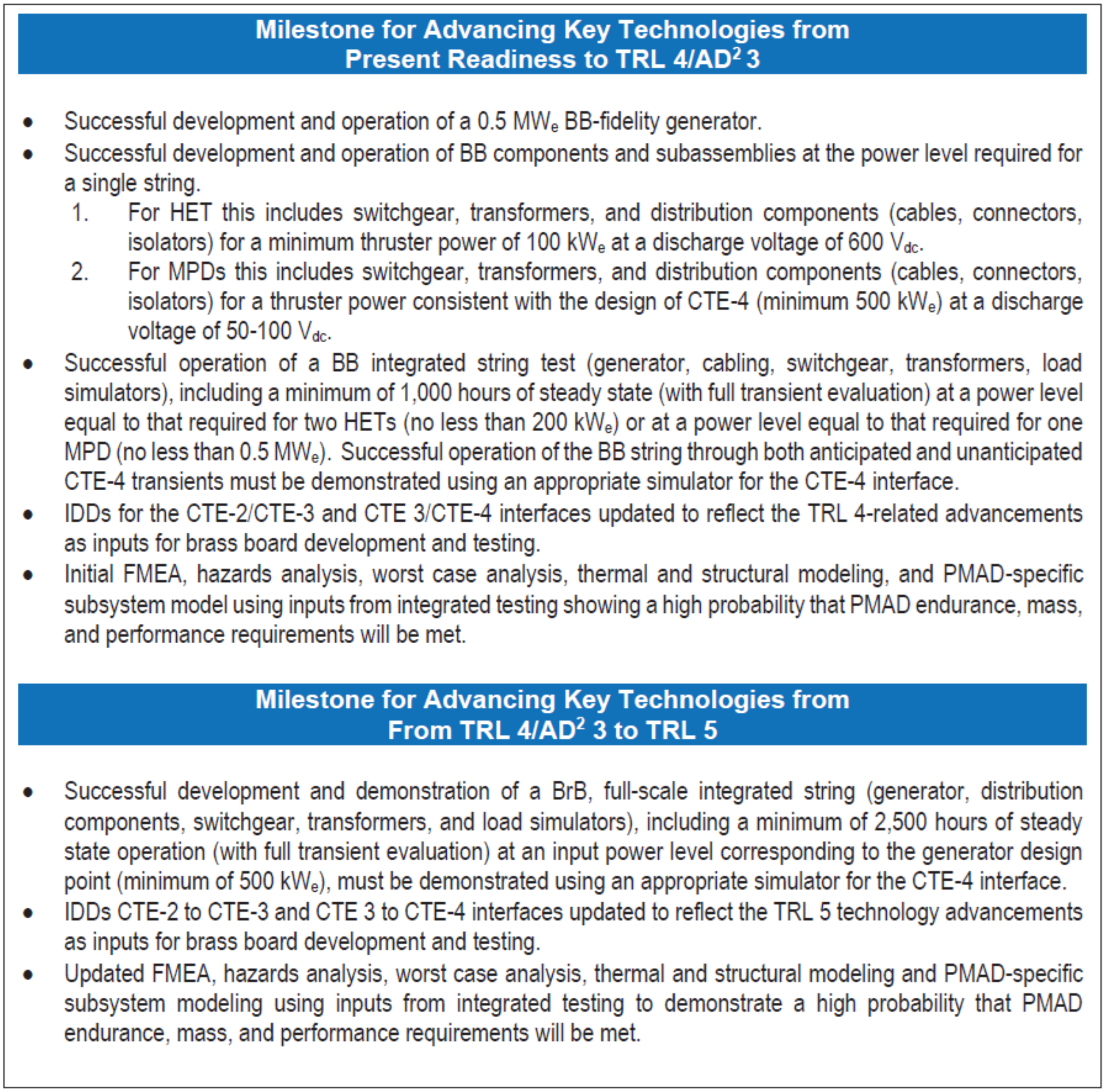
Most of the ongoing work in advanced magnetics and transformers is for EA research programs, and there is fortunately significant overlap between the EA project and the requirements for NEPclass transformers. Many developmental lessons learned from the EA program were presented at the PMAD TIM (ref. [30]) and are transferrable to high-power NEP system development. Table 5.5 shows a list of major gaps and advancement requirements for transformers.

Table 5.5: Major Transformer Technology Gaps and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Magnetic Field Containment	Field containment is a key to high efficiency operation and little work has been done in this area for NEP-class devices. Materials and design trades are required followed by rapid prototyping prior to TRL 4 design selection.
2	Radiation Hardening	No terrestrial or space-based devices at the anticipated power levels are qualified for the anticipated deep space or reactor radiation environments. Rad-tolerant transformers to support either MPD or HET thruster interfaces must be designed, fabricated, and tested. There are many transformers in space and lessons learned from relevant experiences must be captured and documented. The development of specific radiation tolerance requirements followed by the definition and initiation of early materials/component/subassembly testing will be required.
3	Thermal Control	Transformer efficiencies >98% are expected but this implies heat dissipation of 2 to 20 kW_{th} depending on power throughput levels. Simple direct radiation cooling of the transformer will likely not be adequate, and development of an alternate cooling scheme (conductive path, HP, or other options with or without dielectric fill) may be required remove heat to an appropriately scaled radiator.
4	Breakdown Voltage	SME inputs indicate that care in design should be sufficient to prevent breakdown. In-depth analysis for verification and a risk mitigation strategy (e.g., dielectric fluid fill) are required.
5	Mass Optimization	Lessons learned in mass reduction efforts for EA applications should be applied with adaptations required to meet launch environment and in-space usage requirements.
6	Reliability	SOA devices typically have lifetimes beyond those required for NEP. Because in-mission replacement is not possible for NEP, reliability capabilities must be reviewed with modifications and validation to quantify reliability rates as necessary.

5.2 PMAD Technology Advancement Plans

The goal of the SNP program is to develop and demonstrate an end-to-end PMAD subsystem (CTE-3) to TRL 5 in a four-year time frame. This will require first advancing the SOA of the entire subsystem to TRL 4/AD^2 3 in approximately two years. The key milestones in the PMAD advancement strategy are shown in Figure 5.9. All planned development efforts are separable and the project can prioritize them to assure that meaningful progress is still realized if (as likely) full funding is not immediately available.



Milestone for Advancing Key Technologies from Present Readiness to TRL 4/AD^2 3

- Successful development and operation of a 0.5 $\mathrm{MW_e}$ BB-fidelity generator.
- Successful development and operation of BB components and subassemblies at the power level required for a single string.
  1. For HET this includes switchgear, transformers, and distribution components (cables, connectors, isolators) for a minimum thruster power of 100 $\mathrm{kW_e}$ at a discharge voltage of 600 $\mathrm{V_{dc}}$.
  2. For MPDs this includes switchgear, transformers, and distribution components (cables, connectors, isolators) for a thruster power consistent with the design of CTE-4 (minimum 500 $\mathrm{kW_e}$) at a discharge voltage of 50-100 $\mathrm{V_{dc}}$.
- Successful operation of a BB integrated string test (generator, cabling, switchgear, transformers, load simulators), including a minimum of 1,000 hours of steady state (with full transient evaluation) at a power level equal to that required for two HETs (no less than 200 $\mathrm{kW_e}$) or at a power level equal to that required for one MPD (no less than 0.5 $\mathrm{MW_e}$). Successful operation of the BB string through both anticipated and unanticipated CTE-4 transients must be demonstrated using an appropriate simulator for the CTE-4 interface.
- IDDs for the CTE-2/CTE-3 and CTE 3/CTE-4 interfaces updated to reflect the TRL 4-related advancements as inputs for brass board development and testing.
- Initial FMEA, hazards analysis, worst case analysis, thermal and structural modeling, and PMAD-specific subsystem model using inputs from integrated testing showing a high probability that PMAD endurance, mass, and performance requirements will be met.

Milestone for Advancing Key Technologies from From TRL 4/AD^2 3 to TRL 5

- Successful development and demonstration of a BrB, full-scale integrated string (generator, distribution components, switchgear, transformers, and load simulators), including a minimum of 2,500 hours of steady state operation (with full transient evaluation) at an input power level corresponding to the generator design point (minimum of 500 $\mathrm{kW_e}$), must be demonstrated using an appropriate simulator for the CTE-4 interface.
- IDDs CTE-2 to CTE-3 and CTE 3 to CTE-4 interfaces updated to reflect the TRL 5 technology advancements as inputs for brass board development and testing.
- Updated FMEA, hazards analysis, worst case analysis, thermal and structural modeling and PMAD-specific subsystem modeling using inputs from integrated testing to demonstrate a high probability that PMAD endurance, mass, and performance requirements will be met.

Figure 5.9: Key Milestones in the CTE-3 PMAD Advancement Strategy.

To meet these goals, milestone-driven schedules have been developed for 1) the advancement of each MA to BB- and BrB-level fidelity, 2) integrated demonstrations of BB (TRL 4) and BrB fidelity hardware (TRL 5) for durations of 1,000 and 2,500 hours, respectively, with the advancement of modeling capabilities projecting lifetime of $\geq$25,000 hours, and 3) the development or upgrade of any facilities required to support testing. The milestones, with their timing (starting at Q1/Y1 based on ATP) and significance with respect to advancement progress, are shown in Table 5.6 through Table 5.17. Note that the term emulator refers to the equipment required to provide realistic CTE interface interactions during testing (such as those interactions between CTE-2 and CTE-3 or CTE-3 and CTE-4). Detailed IDDs will be developed to guide the development of these emulators and updated at key milestones as development advances. The timelines for advancement shown in Figures 5.10 and 5.11 provide a description of the major milestones, their timing with respect to ATP in Q1/Y1, and a description of the significance of each task with respect to advancement to TRL 4/AD^2 3 or TRL 5. To avoid confusion in schedule interpretation, it is noted that the schedules for TRL 5 MA advancements include milestones late in year 1. This is due to the fact that the MAs must be developed and tested prior to integrated testing at the beginning of year 4 and so lessons learned from early TRL 4 design development must be recognized and incorporated into the TRL 5 design efforts as early as possible.

Table 5.6: Key Generator MA TRL 4 Demonstration Milestones.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Generator & CTE-2 Interface Emulator Design Workshop	CTE3-1.1	Q1/Y1	Generator & interface emulator design evaluations by SMEs with output recommendations for design and fabrication. Preliminary hazard and risk lists reviewed. (to be continuously reviewed and revised as necessary).
Preliminary Design and Fab Options Review	CTE3-1.2	Q1/Y1	Key design decisions (e.g., magnetics, bearings, seals) made, acquisition requirements in place and fabrication options under evaluation.
Initial IDD Draft Complete	CTE3-1.3	Q2/Y1	SME developed interface description document developed, reviewed, and delivered to SNP SE&I lead.
Generator & Emulator Components Ordered	CTE3-1.4	Q3/Y1	Major parts and subassemblies detailed and ordered with specified delivery dates.
Generator Fabrication Complete	CTE3-1.5	Q4/Y1	Fabrication of generator complete and ready for integration and testing.
Interface Emulator & Generator Rotor Delivery	CTE3-1.6	Q4/Y1	BB emulator completed and ready for TRL 4-level bench testing to assure that the emulator/rotor combination is operationally sound early in development.
Interim Generator BB Review	CTE3-1.7	Q4/Y1	SNP-level evaluation to show BB design ready for final fab and assembly.
Preliminary M&S and FMEA Review	CTE3-1.8	Q4/Y1	SME review of all part, component, subassembly, and MA modeling with report to SNP management. SNP review of initial FMEA draft.
Generator Fab & Installation	CTE3-1.9	Q4/Y1	BB hardware fabrication complete and installed in TRL 4 test facility.

Table 5.6: Key Generator MA TRL 4 Demonstration Milestones.

Major Technology Milestones to TRL 4	#	**Timeframe (End Date)**	**Significance**
Generator MA TRR	CTE3-1.10	Q4/Y1	SNP-level readiness review complete – MA testing approved.
Final TRL 4 M&S & FMEA Review	CTE3-1.11	Q4/Y2	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
TRL 4 Testing Complete with SNP-level review	CTE3-1.12	Q4/Y2	SNP-level review of TRL 4 test results to demonstrate MA readiness for TRL 4- level integrated testing.
BB Hardware Delivered for Integration Testing	CTE3-1.13	Q4/Y2	Demonstrated TRL 4 MA delivered for TRL 4 integration testing.
Revised IDD, Risk, FMEA and Hazards Lists Complete	CTE3-1.14	Q4/Y2	Initial IDD revised as necessary for BrB emulator development and delivered to SNP SE&I lead. Risk and hazard list reassessments complete – revisions delivered to SNP.

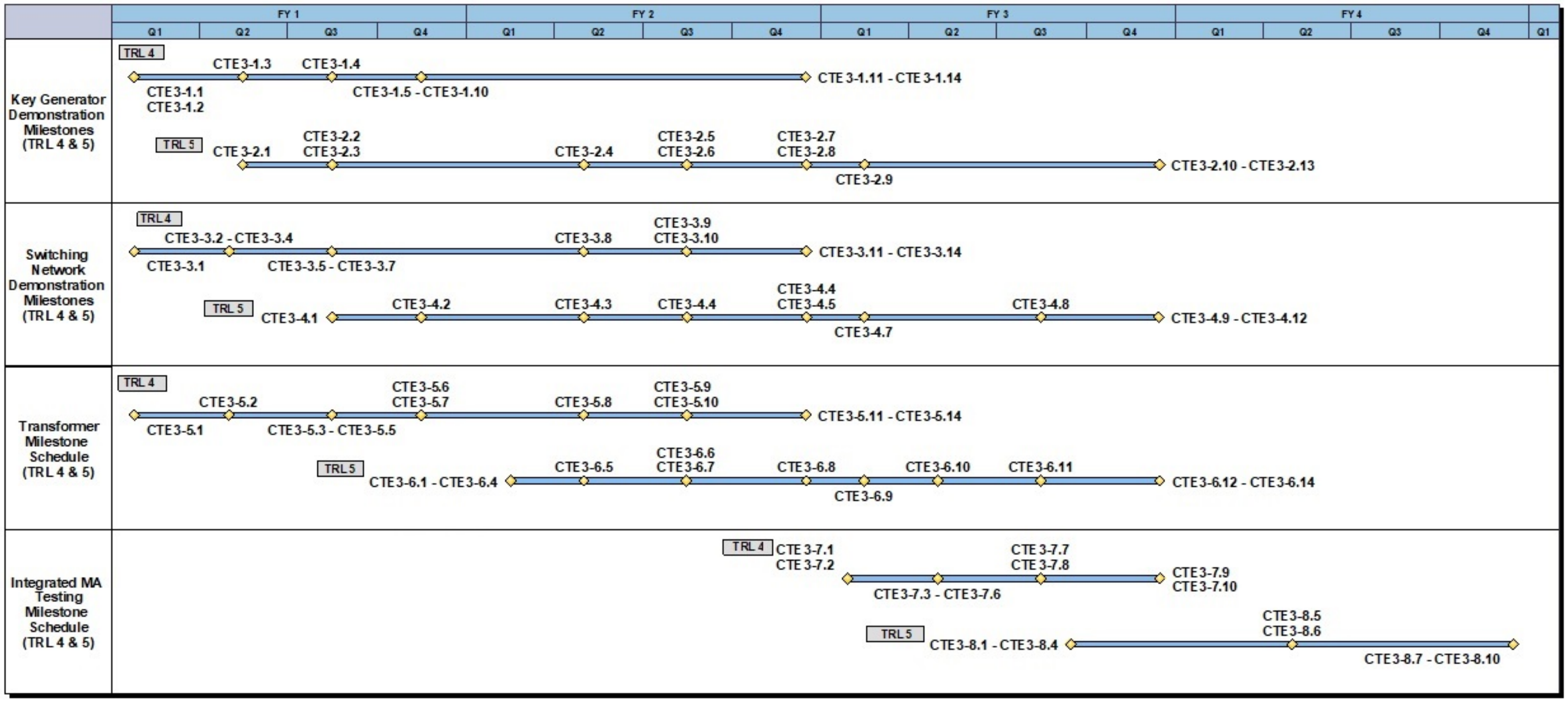


Figure 5.10: CTE 3 Advancement Schedule (tasks CTE3-1 through CTE3-8).

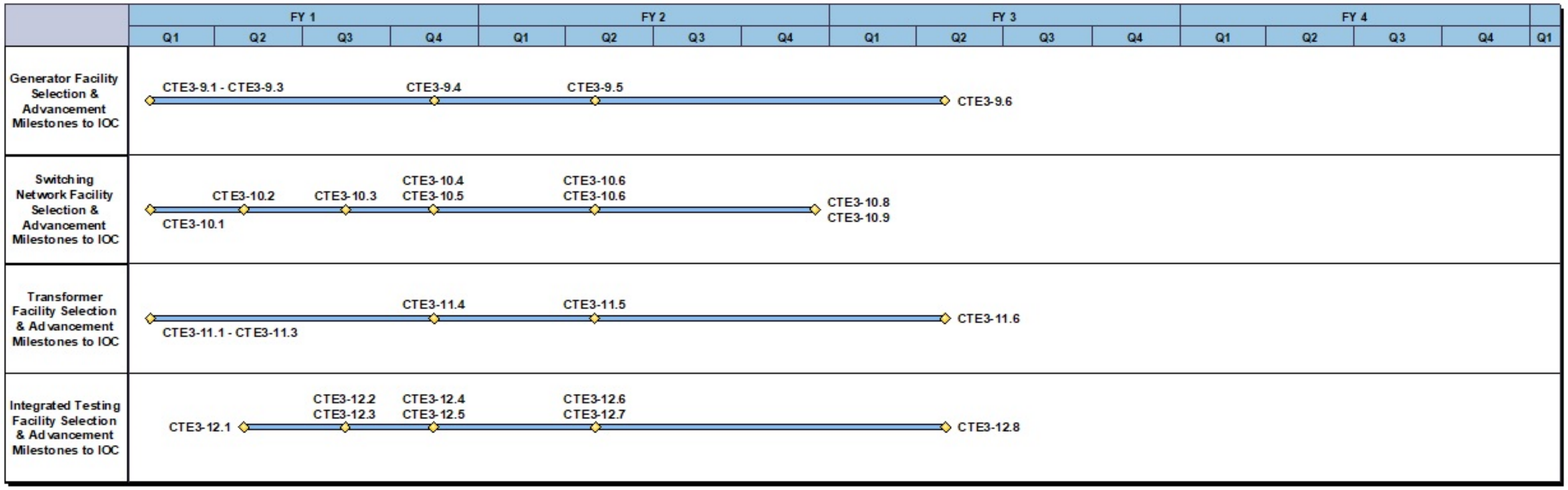


Figure 5.11: CTE 3 Advancement Schedule (tasks CTE3-9 through CTE3-12).

Table 5.7: Key Generator MA TRL 5 Demonstration Milestones.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Generator & Emulator Scaling Issues Assessments	CTE3-2.1	Q2/Y1	Preliminary review to identify major issues (including risks and hazards) associated with scaling to 1 MW_e with recommended research and development for final design decisions in Q4/Y1.
TRL 5 MA Interim Review	CTE3-2.2	Q3/Y1	SNP-level review of design progress with recommendations for design finalization.
Preliminary CTE-2 Interface Emulator IDD Design Review	CTE3-2.3	Q3/Y1	TRL 5 emulator requirements established (e.g., rpm, power, stability), incorporation of TRL 4 lessons learned, design presented.
Preliminary M&S and FMEA Review	CTE3-2.4	Q2/Y2	SME review of all part, component, subassembly, and MA modeling with report to SNP management. Review of updated FMEA.
Final MA and Emulator Design NAR	CTE3-2.5	Q3/Y2	NAR for TRL 5 hardware complete – ready for procurement/fabrication. IDD finalized and transmitted to SNP SE&I lead.
MA & Emulator Design Procurements in Place	CTE3-2.6	Q3/Y2	Designs complete, acquisition strategy in place, hard estimates for deliveries.
BrB Hardware Delivered	CTE3-2.7	Q4/Y2	All required hardware received; fabrication initiated.
BrB MA & Emulator Installation and Form, Fit, Function Tests	CTE3-2.8	Q4/Y2	Fully integrated hardware installed in test facility with benchtop-level shakedown testing complete.
Generator MA TRR	CTE3-2.9	Q1/Y3	SNP-level readiness review complete – MA testing approved.
Final TRL 5 M&S & FMEA Review	CTE3-2.10	Q4/Y3	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
2,500-hour MA Test Complete	CTE3-2.11	Q4/Y3	Testing for MA-level TRL 5 requirements completed.
TRL 5 NAR; Hardware Delivery for Integration Testing	CTE3-2.12	Q4/Y3	Independent review of TRL 5 test results to demonstrate MA readiness for TRL 5- level integrated testing – hardware delivered to integrated testing facility.
Final IDD, FMEA, Risk, and Hazards Lists Complete	CTE3-2.13	Q4/Y3	Initial IDD revised as necessary for BrB emulator development and delivered to SNP SE&I lead. Risk and hazard lists reassessments complete – revisions delivered to SNP.

Table 5.8: Switching Network Major Assembly TRL 4 Milestone Schedule.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Component & MA Design Workshop	CTE3-3.1	Q1/Y1	SME review of available parts, assessed gaps, recommendations made for research and development. Risk and hazard lists reviewed and revised as necessary.
Component Gap Approach Defined	CTE3-3.2	Q2/Y1	Research and development approach to adapting technology (materials, test req's, etc.) complete.
Component Development Approach NAR	CTE3-3.3	Q2/Y1	Independent review of switch development approach and acquisition strategy.
Preliminary M&S and FMEA Review	CTE3-3.4	Q2/Y1	SME review of all part, component, subassembly, and MA modeling with report to SNP management. Review of initial FMEA draft.
Initial IDD Draft Complete	CTE3-3.5	Q3/Y1	SME developed interface description document developed, reviewed and delivered to SNP SE&I lead.
Component Acquisition Plan in Place	CTE3-3.6	Q3/Y1	Acquisition strategy approved with estimated delivery dates.
BB Design Complete with NAR	CTE3-3.7	Q3/Y1	BB design independently reviewed, SNP approval to proceed with acquisitions.
Component Deliveries Complete	CTE3-3.8	Q2/Y2	All hardware for required testing received.
100-Hour Component Test Complete	CTE3-3.9	Q3/Y2	Burn in (infant mortality) test completed to assure part quality.
BB MA TRL 4 TRR	CTE3-3.10	Q3/Y2	SNP-level review of readiness for TRL 4 MA testing.
Final TRL 4 M&S & FMEA Review	CTE3-3.11	Q4/Y2	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
1,000 MA Test Complete	CTE3-3.12	Q4/Y2	BB MA fully demonstrated to TRL 4 requirements.
TRL 4 MA NAR and Delivery for Integrated Testing	CTE3-3.13	Q4/Y2	Independent review of test results to demonstrate MA readiness for TRL 4-level integrated testing.
Revised IDD, Risk, and Hazard Lists Complete	CTE3-3.14	Q4/Y2	Initial IDD revised as necessary for BrB emulator development and delivered to SNP SE&I lead. Preliminary risks and hazards reassessment - revisions complete.

Table 5.9: Switching Network Major Assembly TRL 5 Milestone Schedule.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
TRL 5 Component & BrB Design Workshop	CTE3-4.1	Q3/Y1	SME review of lessons learned in TRL 4 development efforts. Recommendations for modifications (if necessary) for TRL 5 component development efforts. Review of IDD if required. Risk and hazard lists reviewed and revised as required.
Component Acquisition Initiated	CTE3-4.2	Q4/Y1	Research and development approach to adapting technology (materials, test req's, etc.) complete – acquisitions in process with assured delivery dates.
BrB Interim Design Review	CTE3-4.3	Q2/Y2	SNP-level review of BrB development efforts to assure technical quality and schedule reality. IDD (if required) finalized and transmitted to SNP SE&I lead.
Updated M&S and FMEA Review	CTE3-4.4	Q3/Y2	SME review of all part, component, subassembly, and MA modeling with report to SNP management. Review of updated FMEA draft.
Components Delivery & TRR	CTE3-4.5	Q4/Y2	Components delivered and available for testing.
BrB MA Design Complete	CTE3-4.6	Q4/Y2	BrB MA design ready for review.
100-Hour Component Test Complete	CTE3-4.7	Q1/Y3	Burn in (infant mortality) test completed to assure part quality.
BrB MA Fabrication Complete with TRR	CTE3-4.8	Q3/Y3	BrB switching network ready for TRL 5 testing.
Final TRL 5 M&S & FMEA Review	CTE3-4.9	Q4/Y3	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
2,500-hour MA Test Complete	CTE3-4.10	Q4/Y3	Testing for MA-level TRL 5 requirements completed.
TRL 5 NAR and Delivery for Integrated Testing	CTE3-4.11	Q4/Y3	NAR to assure MA-level TRL 5 achieved & hardware delivered for integrated testing.
Final IDD, FMEA, Risk, and Hazard Lists Complete	CTE3-4.12	Q4/Y3	Initial IDD revised as necessary and delivered to SNP SE&I lead. Preliminary risks and hazards reassessment - revisions complete.

Table 5.10: Transformer Major Assembly TRL 4 Milestone Schedule.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Transformer & CTE-4 Interface Emulator Workshop	CTE3-5.1	Q1/Y1	SME review of available parts, gaps assessed, recommendations made for research and development. Preliminary IDD developed (if required). Risk and hazard lists reviewed and revised as required.
Transformer Core Design Options	CTE3-5.2	Q2/Y1	Preliminary designs (potentially multiple options for different PMAD and CTE-4 interface selections) developed for in-depth analysis.
Initial IDD Draft Complete	CTE3-5.3	Q3/Y1	SME developed interface description document developed, reviewed and delivered to SNP SE&I lead.
Preliminary M&S and FMEA Review	CTE3-5.4	Q3/Y1	SME review of all part, component, subassembly, and MA modeling with report to SNP management. Review of initial FMEA draft.
Transformer Design Selection	CTE3-5.5	Q3/Y1	SME selection of BB transformer design complete with SNP-level review.
Emulator Development Complete	CTE3-5.6	Q4/Y1	Emulator finished and available for TRL 4 MA testing.
MA Midterm NAR for Fabrication	CTE3-5.7	Q4/Y1	Independent review of transformer design, emulator sufficiency, and test plans.
Fabrication Interim Review	CTE3-5.8	Q2/Y2	SNP-level progress review (technical readiness and schedule credibility).
MA Hardware Fabrication Complete	CTE3-5.9	Q3/Y2	SNP-level approval of MA hardware design - transformer hardware ready for TRL 4 testing.
MA TRL 4 TRR	CTE3-5.10	Q3/Y2	SNP-level test plan review.
Final TRL 4 M&S & FMEA Review	CTE3-5.11	Q4/Y2	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
MA TRL 4 Test Complete	CTE3-5.12	Q4/Y2	Testing complete – data available for NAR review.
TRL 5 NAR – MA Delivered for Integration Testing	CTE3-5.13	Q4/Y2	NAR to assure MA-level TRL 4 achievement – hardware available for integration testing.
Revised IDD, FMEA, Risk, and Hazards lists Complete	CTE3-5.14	Q4/Y2	Initial IDD revised as necessary and delivered to SNP SE&I lead. Risk and hazard lists reassessments complete – revisions delivered to SNP.

Table 5.11: Transformer Major Assembly TRL 5 Milestone Schedule.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Transformer & CTE-4 Interface Emulator Workshop	CTE3-6.1	Q1/Y2	SME review of lessons learned in TRL 4 development efforts. Recommendations for modifications (if necessary) for TRL 5 transformer development efforts. Risk and hazards lists reviewed and updated as necessary.
Transformer Design Selected	CTE3-6.2	Q1/Y2	TRL 5 transformer design chosen by SME's – acquisition requirements understood.
BRB Interim Design Review	CTE3-6.3	Q1/Y2	TRL 5 requirements established, emulator strategy complete, incorporation of TRL 4 lessons learned, preliminary design presented. IDD developed.
MA Component Selection Initiated	CTE3-6.4	Q1/Y2	All parts and subassemblies defined; acquisition strategy in place.
Preliminary M&S and FMEA Review	CTE3-6.5	Q2/Y2	SME review of all part, component, subassembly, and MA modeling with report to SNP management. Review of initial FMEA draft.
MA Design Complete w/NAR	CTE3-6.6	Q3/Y2	Independent review for transformer fabrication readiness.
MA Component Acquisition Complete	CTE3-6.7	Q3/Y2	All parts and subassemblies in hand for fabrication.
Interface Emulator Complete	CTE3-6.8	Q4/Y2	CTE-4 interface hardware ready for TRL 5 MA-level testing based on IDD specifications.
MA Fabrication Complete w/NAR	CTE3-6.9	Q1/Y3	Transformer full fabricated, bench testing complete, independent review for TRL 5 test readiness complete.
MA TRL 5 TRR	CTE3-6.10	Q2/Y3	SNP-level test plan review.
Final TRL 5 M&S & FMEA Review	CTE3-6.11	Q3/Y3	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
2,500-hour MA Test Complete	CTE3-6.12	Q4/Y3	2,500-hour MA test for TRL 5 complete – data available for NAR.
TRL 5 MA NAR – MA Delivered for Integration Testing.	CTE3-6.13	Q4/Y3	MA testing, model comparisons complete, independent evaluation for TRL 5, equipment ready for integrated testing.
Final IDD, FMEA, Risk, and Hazard Lists Complete	CTE3-6.14	Q4/Y3	Initial IDD revised as necessary delivered to SNP SE&I lead. Preliminary risks and hazards reassessment - revisions complete.

Table 5.12: Integrated MA Testing TRL 4 Milestone Schedule.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
TRL 4 MA Hardware Delivered – Internal MA to MA IDDs complete	CTE3-7.1	Q1/Y3	Tested MA hardware delivered to TRL 4 integrated testing site. MA to MA IDDs developed and delivered to SNP CTE lead.
Hardware Inspection. M&S and FMEA Reviews	CTE3-7.2	Q1/Y3	Independent review of readiness of delivered hardware. Preliminary integrated system M&S and FMEA reviews.
Hardware Integration & Acceptance Testing	CTE3-7.3	Q2/Y3	All 3 MA's integrated into BB PMAD testbed with preliminary 'form, fit, function' checks.
Integrated Subsystem TRR	CTE3-7.4	Q2/Y3	SNP-level test readiness review.
500 kW_e Shakedown Test Complete	CTE3-7.5	Q2/Y3	Short (burn-in) test to assure integrated operational readiness before full testing.
Integrated Endurance Test TRR	CTE3-7.6	Q2/Y3	Independent readiness review for authority to proceed to full 1,000-hour integrated test.
Final TRL 4 M&S & FMEA Review	CTE3-7.7	Q3/Y3	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
TRL 4 Integrated Test Complete	CTE3-7.8	Q3/Y3	TRL 4-level testing with model comparison and updated FMEA.
TRL 4 Advancement NAR	CTE3-7.9	Q4/Y3	Independent review to demonstrate that TRL 4 has been achieved.
Revised IDD, FMEA, Risk, and Hazard Lists Complete	CTE3-7.10	Q4/Y3	Initial IDD revised as necessary and delivered to SNP SE&I lead. Preliminary risks and hazards reassessment - revisions complete.

Table 5.13: Integrated MA Testing TRL 5 Milestone Schedule.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
TRL 5 MA Hardware Delivered and MA to MA IDDs Developed	CTE3-8.1	Q1/Y4	Tested MA hardware delivered to TRL 5 integrated testing site. MA to MA IDDs complete.

Table 5.13: Integrated MA Testing TRL 5 Milestone Schedule.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Hardware Inspection. Updated M&S and FMEA Reviews	CTE3-8.2	Q1/Y4	Pre-integration MA hardware evaluation. Review of updated integrated M&S and FMEA complete.
Hardware Integration and Acceptance	CTE3-8.3	Q1/Y4	All 3 MA's integrated into BrB PMAD testbed with preliminary 'form, fit, function' checks.
Integrated subsystem TRR	CTE3-8.4	Q1/Y4	SNP-level review and authority to proceed to testing.
MWe Shakedown Test Complete	CTE3-8.5	Q2/Y4	Short test to assure integrated operational readiness before full testing.
Integrated Endurance Test TRR	CTE3-8.6	Q2/Y4	SNP-level review for authority to proceed to full 2,500-hour integrated test.
Final TRL 5 M&S & FMEA Review	CTE3-8.7	Q4/Y4	M&S updated with MA test data, FMEA updated – documents prepared for NAR.
TRL 5 Integrated Testing Complete	CTE3-8.8	Q4/Y4	2,500-hour test complete, data available to support NAR.
TRL 5 Advancement NAR	CTE3-8.9	Q4/Y4	Independent review for TRL 5 acceptance.
Final IDD, FMEA, Risk, and Hazard Lists Complete	CTE3-8.10	Q4/Y4	Initial IDD revised as necessary and delivered to SNP SE&I lead. Preliminary risks and hazards reassessment - revisions complete.

Table 5.14: Generator Facility Selection and Advancement Milestones to Initial Operating Condition (IOC).

Milestones	**#**	**Timeframe (End Date)**	**Significance**
TRL 4 Facility Workshop	CTE3-9.1	Q1/Y1	SME assessment of facility requirements and survey of available facilities for TRL 4 development
TRL 4 Facility Selection	CTE3-9.2	Q1/Y1	Facility selected for TRL 4 testing – upgrades defined if needed
TRL 5 Facility Workshop	CTE3-9.3	Q1/Y1	SME assessment of facility requirements and survey of available facilities for TRL 5 development
TRL 4 Facility IOC	CTE3-9.4	Q4/Y1	TRL 4 MA test facility operational

Table 5.14: Generator Facility Selection and Advancement Milestones to Initial Operating Condition (IOC).

Milestones	**#**	**Timeframe (End Date)**	**Significance**
TRL 5 Facility Selection	CTE3-9.5	Q2/Y2	Facility selected for TRL 5 testing – upgrades defined if needed
TRL 5 Facility IOC	CTE3-9.6	Q2/Y3	TRL 5 MA test facility operational

Table 5.15: Switching Network Facility Selection and Advancement Milestones to IOC.

Milestones	**#**	**Timeframe (End Date)**	**Significance**
TRL 4 & 5 Component and MA Workshop	CTE3-10.1	Q1/Y1	SME assessment of facility requirements and survey of available facilities for TRL 4 development
TRL 4 & 5 Facility Selection	CTE3-10.2	Q2/Y1	Facility selected for TRL 4 & 5 component testing – upgrades defined if needed
Facility Progress Reviews	CTE3-10.3	Q3/Y1	SNP-level review for component testing facility selections
TRL 4 Component Facility IOC	CTE3-10.4	Q4/Y1	TRL 4 component facility ready for testing
Facility Progress Reviews	CTE3-10.5	Q4/Y1	SNP-level review for TRL 4 MA testing facility selections
TRL 4 MA Facility IOC	CTE3-10.6	Q2/Y2	TRL 4 MA test facility operational
Facility Progress Reviews	CTE3-10.7	Q2/Y2	SNP-level review for TRL 5 MA testing facility selections
TRL 5 Component Facility IOC	CTE3-10.8	Q4/Y2	TRL 5 component test facility operational
TRL 5 MA Facility IOC	CTE3-10.9	Q4/Y2	TRL 5 MA test facility operational

Table 5.16: Transformer Facility Selection and Advancement Milestones to IOC.

Milestones	#	**Timeframe (End Date)**	**Significance**
TRL 4 Facility Workshop	CTE3-11.1	Q1/Y1	SME assessment of facility requirements and survey of available facilities for TRL 4 development
TRL 4 Facility Selection	CTE3-11.2	Q1/Y1	Facility selected for TRL 4 testing – upgrades defined if needed
TRL 5 Facility Workshop	CTE3-11.3	Q1/Y1	SME assessment of facility requirements and survey of available facilities for TRL 5 development
TRL 4 Facility IOC	CTE3-11.4	Q4/Y1	TRL 4 MA test facility operational
TRL 5 Facility Selection	CTE3-11.5	Q2/Y2	TRL 5 Facility selected – upgrades defined if needed
TRL 5 Facility IOC	CTE3-11.6	Q2/Y3	TRL 5 MA test facility operational

Table 5.17: Integrated Testing Facility Selection and Advancement Milestones to IOC.

Milestones	#	**Timeframe (End Date)**	**Significance**
TRL 4 Integrated Test Requirements Workshop	CTE3-12.1	Q2/Y1	SME assessment of facility requirements and survey of available facilities for integrated TRL 4 development testing
TRL 4 Integrated Test Facility Selection	CTE3-12.2	Q3/Y1	Facility for TRL 4-level integrated testing selected – upgrades defined if needed
TRL 5 Integrated Test Requirements Workshop	CTE3-12.3	Q3/Y1	SME assessment of facility requirements and survey of available facilities for integrated TRL 5 development testing
TRL 4 Facility Progress Review	CTE3-12.4	Q4/Y1	SNP-level review for TRL 4 integrated testing facility selection
TRL 5 Integrated Test Facility Selection	CTE3-12.5	Q4/Y1	Facility for TRL 5-level integrated testing selected – upgrades defined if needed
TRL 4 Facility IOC	CTE3-12.6	Q2/Y2	TRL 4 integrated test facility operational
TRL 5 Facility Progress Review	CTE3-12.7	Q2/Y2	SNP-level review for TRL 5 integrated testing facility selection
TRL 5 Facility IOC	CTE3-12.8	Q2/Y3	TRL 5 integrated test facility operational

Major objectives planned for advancement of the SOA to TRL 5 (on the CTE level) in the proposed four-year timeframe include:

- Advancement of the key technologies on the MA level to TRL 4/AD^2 3 over the first two years. This must include component advancement and testing (including burn-in testing) as required. The schedules show these advancements occurring independently in dedicated facilities. In fact, there may be substantial overlap to negotiate with respect to both facility usage and early integrated testing. SNP-lead SMEs will coordinate test plans and exploit synergies wherever possible.

- TRL 5 advancement of each individual MA (including early procurements and facility upgrade planning) starting at the earliest practical time (estimated in schedules). As with the progression to TRL 4/AD^2 3, the anticipated timeframe for advancement is two years beginning (mostly) at the end of the first year.

- Delivery of BB-fidelity TRL 4/AD^2 3 and BrB-fidelity TRL 5 hardware for integrated testing at the end of year 2 and the end of year 3, respectively. Facility IOC dates and major TRRs occur in the same timeframe. The integrated TRL 5 testing (at minimum) must be performed at a vacuum facility, and it is possible that this will need to be performed using a fully operational EPS for proper CTE-4 emulation.

- The development and implementation of a component research and development plan to provide long-term testing of key materials and components (e.g., wire insulation) in expected environments for endurance evaluations over longer periods than possible with the fast-paced MA development.

- Review and revision of CTE-3 plan to ensure that well defined and up to date IDDs are in place and that vehicle level integration implications are understood – i.e., an engineering assessment to ensure that hardware integration will be feasible and practical.

It should be noted that while the schedules shown are ambitious, the test sequences are planned with significant schedule margin. For example, the 2,500-hour integrated testing to meet TRL 5 acceptance criteria is scheduled in a full 3Q block (9 months/6,500 hours).

5.3 CTE-3 Technology Advancement Risks

While a rigorous risk analysis will be performed during the course of the maturation effort, including an FMEA that will be updated to increasing levels of fidelity as the technical program progresses, SNP SME's have performed preliminary risk evaluations for many technical aspects of the PMAD system as a part of the development of this TMP. It is noted that the FMEA will include the CTE-2 and CTE-4 interfaces to ensure that there is a full accounting of impacts related to failure modes due to the coupling between those subsystems and CTE-3. A preliminary risk assessment of the 'Top 5' risks identified to date is shown in Table 5.18. The entries include the risk title, statement, assessment, and planned mitigation strategies for each risk. These risks were developed using NASA's standard risk scale for consequence and likelihood as taken from GPR 7120.4D, Risk Management Reporting, which uses the standard risk ranking shown graphically in Figure 5.19.

Table 5.18: 'Top 5' PMAD system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Table 5.19: PMAD 'Top 5' Risk Ranking Likelihood and Consequence Span.

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PMAD-1	Generator Fabrication & Assembly Issues	Issues with meeting tolerances and development of assembly procedures delay 500 kW_e-1.0 MW_e-class rotor/stator readiness	T	3	3	9	SME design & NAR of TRL 4 rotor/stator combination coupled with a rapid prototyping approach (especially for the rotor). Development of alternate design and assembly processes. Schedule margin sufficient to permit at least one "failure cycle."
PMAD-2	TRL 4 Brayton Emulator Capability Issue	Inability to develop an acceptable Brayton shaft emulator impedes generator development	T	3	2	6	SME design & NAR of TRL 4 emulator coupled with early testing. Development of alternate design to fabrication readiness. Schedule margin sufficient to permit at least one "failure cycle."

Table 5.19: PMAD 'Top 5' Risk Ranking Likelihood and Consequence Span.

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PMAD-3	Switchgear Technology Qualification Issues	SOA switchgear does not fulfill NEP mission requirements (frequency of operation, launch, radiation, vacuum environment, etc.).	T	3	2	6	Early component testing to demonstrate compatibility with design operating frequency (initial nominal value of 2 kHz). Early design optimization for launch & space environments with at least two alternate configurations derived from two separate sources. Thorough component testing at the TRL 4 level with schedule margin to assess multiple configurations.
PMAD-4	CTE-3/CTE-4 Interface Emulator Issues	CTE-4 interface emulator fails to adequately replicate transient and steady state characteristics of plasma thruster operation.	T	2	3	6	Early interface designs (at least two) by SMEs with NAR-informed selection for TRL 4 hardware. Integrate with actual TRL 5 hardware (co-locate CTE-3 and CTE-4 development if necessary). Schedule margin sufficient for at least one "failure cycle."

Table 5.19: PMAD 'Top 5' Risk Ranking Likelihood and Consequence Span.

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PMAD-5	Inability to scale 500 kW_e generator design to 1 MW_e	Issues associated with space rating requirements prevent scaling required to realize a single string MW_e "building block."	T	2	2	4	Early (Y1) scaling study and redesign with NAR following 500 kW_e development and incorporation of lessons learned. Fallback option of parallel, ganged 500 kW_e units for 1 MW_e building block. Schedule margin sufficient to permit a second attempt if the first attempt does not meet performance metrics.

5.4 PMAD Maturation Summary

This section provided the advancement plan for the PMAD subsystem of a high-power NEP system. The plan advances the generator, switching network, and transformer technologies required for a MW_e-class PMAD subsystem through TRL 4 to TRL 5 both at the major assembly level and in a fully integrated configuration. The plan includes a milestone-driven schedule that, if fully funded and executed, will result in a TRL 5 PMAD subsystem (CTE-3 in the overall NEP system) that has undergone rigorous non-advocate review for confirmation of TRL advancement at key milestones and that possesses a clear path to system-level implementation. In addition to the demonstrated hardware, detailed descriptions of the technology advancements and updated IDDs will be available for use in "beyond TRL 5" NEP system and vehicle integration planning. While the plan was developed for execution over a four-year time frame to meet a late 2030s need date, the technology advancement tasks are separable by design so that meaningful, prioritized progress through demonstrations with relevant hardware can be accomplished as resources become available. The focused research and development described in this section provides NASA with a path to quantified assessments of all key PMAD technologies needed to support informed decisionmaking regarding the efficacy of NEP system technology for human spaceflight and large robotic missions.

Chapter 6

Advancement Plan – CTE-4: Electric Propulsion Subsystem (EPS)

The EPS comprising CTE-4 includes the thruster(s), all power processing components/ subsystems downstream of the transformer output(s) of the PMAD subsystem (CTE-3), the propellant handling system including propellant tanks and the propellant flow control subsystem, and any associated mounting structures and gimbaling mechanisms. A simplified block diagram can be seen below in Figure 6.1. The figure shows multiple thruster options based on most likely selections from SME inputs.

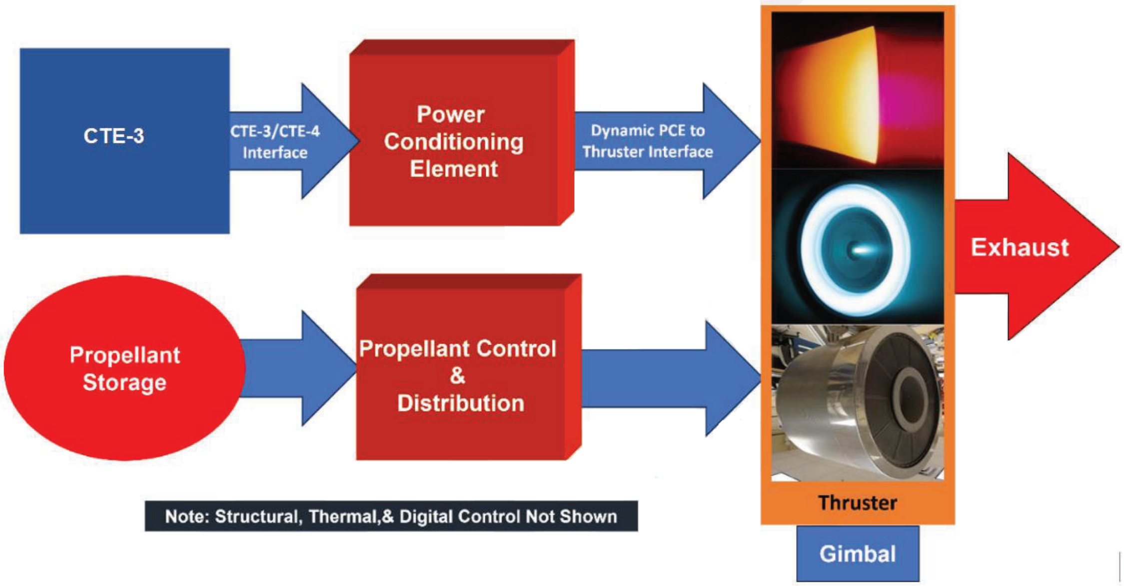


Figure 6.1: Simplified block diagram of the electric propulsion subsystem.

The diagram shows three major assemblies (MA) starting with the power conditioning element (PCE) at the CTE-3/CTE-4 interface. At this interface, AC power at a voltage optimized for the selected thruster technology is received and conditioned for delivery to the thruster. Both conventional power processing units and direct drive units are being considered and are discussed in detail in this section. In either case, AC-to-DC conversion is required on the CTE-4 side of the interface. It is noted that the PCE is composed of both a Power Conditioning Unit (PCU) and a Digital Control Interface Unit (DCIU) to perform command and control functions. While essential, DCIU technology is well-understood and considered straightforward engineering (see for example, ref. [140]) while the PCU is challenging and represents a major focus for technology maturation and advancement. The thrusters (and associated hardware like gimbals) comprise the second MA and multiple options are considered. For the proposed 1 $\mathrm{MW_e}$ building blocks, thruster options range from single, $\mathrm{MW_e}$-class devices to a number of individual thrusters in the 100-250 $\mathrm{kW_e}$-class that, when arranged in a thruster bank, process power levels of 1 $\mathrm{MW_e}$. Details on the various thruster types are given later in this section. The other MA is comprised of the propellant storage tankage and propellant feed systems. These systems are dependent upon the thruster and propellant type selected (e.g., Li or Xe) and are described as part of the thruster discussions.

Over the past three decades, solar electric propulsion (SEP) system development and infusion into flight missions has flourished. In 1992 the 1 $\mathrm{kW_e}$-class hydrazine arcjet thruster first flew for northsouth station keeping (NSSK) on a commercial geostationary comsat, breaking a major barrier and establishing SEP as a demonstrated technology for operational application. Since then, there have been hundreds of arcjet, Hall, and ion thrusters flown by the commercial and government entities (ref. [105]). Standouts among these include the 2.3 $\mathrm{kW_e}$ NASA Solar Technology Application Readiness (NSTAR) ion engine flown on the Deep Space 1 (ref. [141]) and NASA Dawn (ref. [106]) missions (the Dawn EPS presently holding the record for in-space Δv imparted to a spacecraft), the 30 $\mathrm{kW_e}$-class arcjet flown on the Air Force Electric Propulsion Space Experiment (ESEX) that demonstrated PPU technology potentially applicable to high-power/high-current thruster systems (ref. [142]), "all-electric" geostationary comsats (ref. [143]), and the 4.5 $\mathrm{kW_e}$ Hall system on the Advanced Extremely High Frequency (AEHF) geostationary constellation (ref. [144]). On the first AEHF mission the electric thrusters were successfully used for emergency orbit-raising, saving the spacecraft and placing it into the proper orbit after a failure of the chemical insertion system (ref. [143]). In addition to these successful applications, NASA's Advanced Electric Propulsion System (AEPS) program is developing 12.5 $\mathrm{kW_e}$ Hall thrusters for the PPE for the lunar Gateway program (ref. [145]). These developments show the increasing capabilities of EP as additional power becomes available on spacecraft, with these successes laying the groundwork for much higher power NEP-class missions.

NASA has intermittently invested resources in high-power NEP system development over the past six decades and major benefits have been projected in many mission architectures and systems analyses for spacecraft using NEP (refs. [18, 20, 21, 22, 23, 24, 25, 26, 27, 65, 145]). Coordinated technical efforts to define and develop high-power NEP systems have included, for example, the 30 $\mathrm{kW_e}$ hydrogen arcjet system of the SNAP-8 program in the 1960s (refs. [2, 3]), multiple technologies developed in the 1990s SEI (refs. [9, 10, 14]) that was performed in parallel with the SP-100 reactor development program (ref. [11]), and early 2000s work on the JIMO/Project Prometheus program (refs. [15, 17]). In addition, basic research and development on high-power thrusters (e.g., ion [146], Hall [147, 148, 149, 150, 151, 152, 153, 154], MPD [155, 156, 157, 158]), and the Variable Specific Impulse Magnetoplasma Rocket [159]) has received varying levels of sporadic funding over the past three decades.

Unfortunately, none of these development efforts have been sufficient to advance EPS technologies to the level necessary to support a down-select decision to a specific thruster system for MW_e-class missions. This conclusion is supported by recent independent reviews conducted by the NESC (ref. [28]) and the NASEM (ref. [29]). To address this gap and demonstrate that EP systems can be used in MW_e NEP applications, SNP is pursuing a focused research and development program designed to advance EPS TRL/AD^2 levels in a stepwise fashion from their current values to TRL 4/AD^2 3 and then TRL 5.

In keeping with the robust SE&I philosophy described in the Introduction, a detailed Interface Description Document (IDD) will be developed for the external CTE-3/CTE-4 interface. Preliminary descriptions of this interface are discussed in this section but a stand-alone IDD will be developed by SNP SMEs and provided to the SNP CTE-4 lead after discussion at the opening workshop. This IDD will be reviewed by SNP, circulated for SME evaluation if required, and then finalized and kept by the SNP SE&I lead. The document will be reviewed and revised as needed at each major relevant milestone, including as part of the NARs planned for technology advancement verification. with NAR approval of the IDD as a condition for advancement. In addition, IDD's will be generated for each MA-to-MA interface to ensure compatibility as EPS breadboard and brassboard development efforts progress. Because the PCU-to-thruster interface is dynamic, it is anticipated that this MA-to-MA interface will require the same level of rigor as the external CTE-3/CTE-4 interface. Finally, thermal control for each MA will require careful consideration (e.g., a MW_e-class PCU operating at 95% efficiency will require the rejection of 50 kW). For the purposes of the TMP, development efforts for each MA must include an accounting for how thermal management will be accomplished in a way that is compatible with vehicle integration. The need for separate IDD's for thermal management within CTE-4 will be discussed at the opening workshop and IDD's will be developed if deemed necessary. All CTE-4 specific IDDs will be maintained by the CTE lead and reviewed with the SNP SE&I lead and/or SMEs as needed.

All applicable standards, including those required for human rating, will be identified at the opening workshop and applied as appropriate so the brassboard hardware developed to achieve TRL 5 will translate to TRL 6/prototype/flight-like designs without requiring any appreciable additional research and maturation. NAR validation of this extensibility to higher TRL development and implementation will also be a condition for technology advancement. Additionally, at the TRL 4 and TRL 5 NARs, the latest CTE-4 technology status will be combined with the latest results from the development of all the other CTEs and incorporated into a continuously evolving conceptual vehicle configuration assessment to ensure that the combined CTEs will lead to a feasible and practical vehicle configuration.

SNP's research and development program focuses on hardware development and testing backed by extensive M&S efforts. The proposed M&S activities will develop high-fidelity models as required to 1) understand the controlling physical parameters and operational modes within the thruster system, 2) demonstrate thruster system/spacecraft compatibility, and 3) project required EPS endurance supported by validation data acquired through sub-scale (SS) and full scale (FS) testing. SNP used inputs from a series of TIMs (ref. [30]), from discussions with SMEs, and from an NESC review on NEP subsystem maturity levels (ref. [28]) to determine the SOA and the research and development directions required for project success. Based on these inputs, SNP has selected Xe-fed Hall thrusters and Li-fed

MPD thrusters as the most likely electric propulsion options that can be ready in the near term to support high-power NEP missions. Examples of operating high-power MPD and Hall thrusters are shown in Figure 6.2.

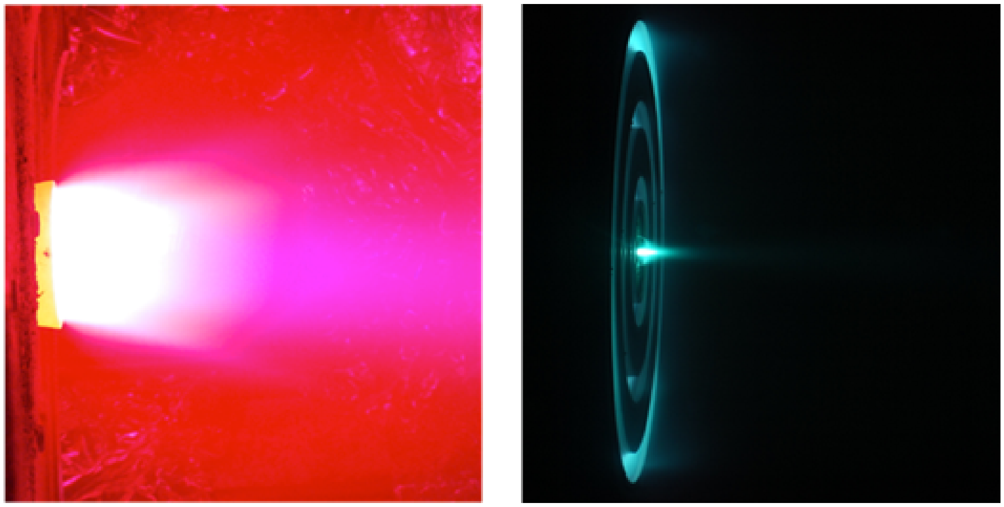


Figure 6.2: Li-fed MPD (left) and Xe-fed Hall (right) thrusters in operation.

The propulsive performance of these two technologies are illustrated in Figure 6.3 (ref. [19]). These curves are consistent with relevant, documented performance test data (refs. [152, 153, 154, 155]). It is noted that a range of ±5% (absolute) has been used in all performance modeling to evaluate the impacts of performance variation for both Hall and MPD systems. The MPD performance curve is derived from data obtained through endurance testing at 500 kW_e (ref. [155]) – it is anticipated that performance at 1 MW_e (target for the present effort) would be slightly better than what is shown. The Hall thruster curve is derived from short duration testing at 100 kW_e and below (refs. [152, 153]). This is the power level used in recent studies (see, for example, refs. [18, 19, 20, 21, 22, 23, 24, 25, 26, 27]) – slightly higher performance may be possible using higher power devices and an early evaluation of the optimal power level is planned at the outset of the program.

For the focused research and development efforts, a CTE-4-specific WBS to be used for EPS development is shown in Figure 6.4. While the thruster selection will influence the advancement activities in each WBS element, the required elements are, in general, not thruster dependent.

The background, SOA, technology gaps, SNP technology advancement plans, and preliminary development risk assessment and mitigation plans are presented in this Chapter for both Hall thrusters and MPD thrusters.

Both exogenous hazards (e.g., micro-meteoroid strikes) to the spacecraft and physical hazards in development testing will be considered. A preliminary list of these will be generated by SNP SME's and refined as the development efforts progress. Necessary activities to mitigate exogenous hazards will be included under the appropriate technology development effort shown in the WBS (Figure 6.4). For example, technology development to mitigate the impacts of cosmic radiation on PCU components would be performed under the PCU Element of the WBS. Modeling required and tracking of the advancement will be carried under

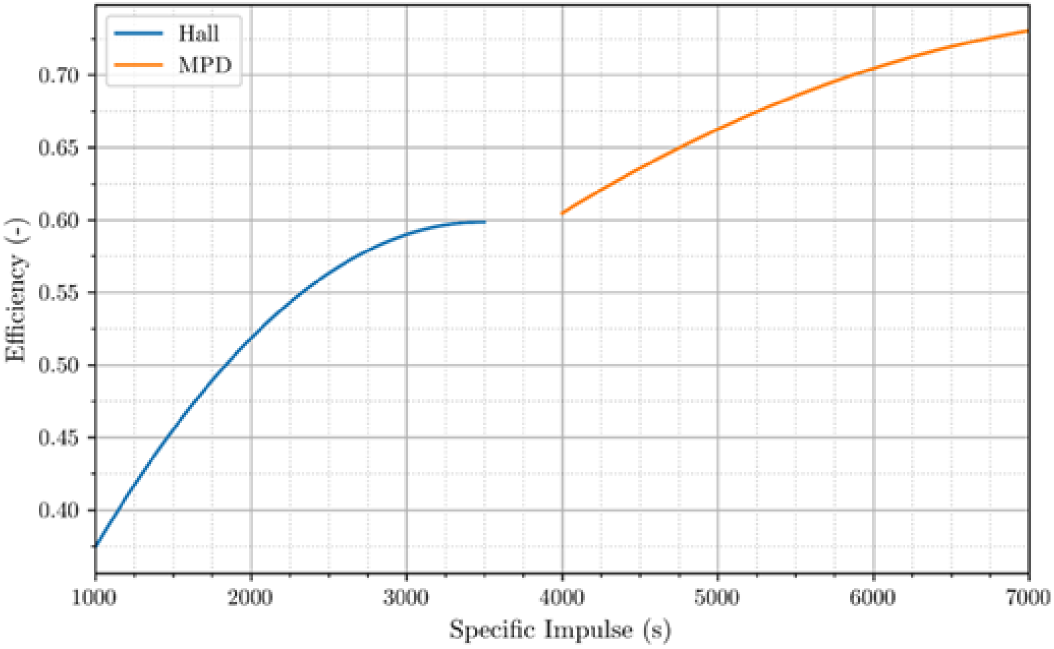


Figure 6.3: Hall and MPD Thruster Performance Curves (ref. [19]).

either/or the “Environments” and “FMEA development” boxes and this determination will be made in consultation with the SNP SE&I lead. Safety hazards, such as the inherent danger of pumping high temperature liquid metals, will be addressed through project-managed Safety and Mission Assurance processes.

6.1 Hall Technology Background, State-of-Art, and Technology Gaps

A schematic diagram of a notional Hall thruster is shown in Figure 6.5. Operationally, an electric potential is fixed between the cathode (external electron source in the figure) and the anode (left in figure where neutral propellant is injected). Propellant is injected into the main channel where a radial magnetic field is applied. Electrons emitted by the cathode are trapped by the magnetic field creating an azimuthal Hall current that ionizes the propellant atoms via collision. These ions, which are not magnetized owing to their large mass, are then accelerated out the open end of the device by the applied electric field to generate thrust (ref. [160]).

While multiple thruster designs exist, most fall into two classes – the stationary plasma thruster (SPT) and the thruster with anode layer (TAL) (ref. [161]). Both employ the same acceleration phenomena of trapping electrons through the Hall effect to concentrate the electric field to a small region within the thruster channel. Hall thrusters operate with relatively low plasma densities and are typically optimized in the specific impulse (I_{sp}) range of 1500 to 3000 s with efficiencies between 40 to 60%. Hall systems are of high interest due to their simplicity of operation, projected performance, and potential for long lifetime at NEP-

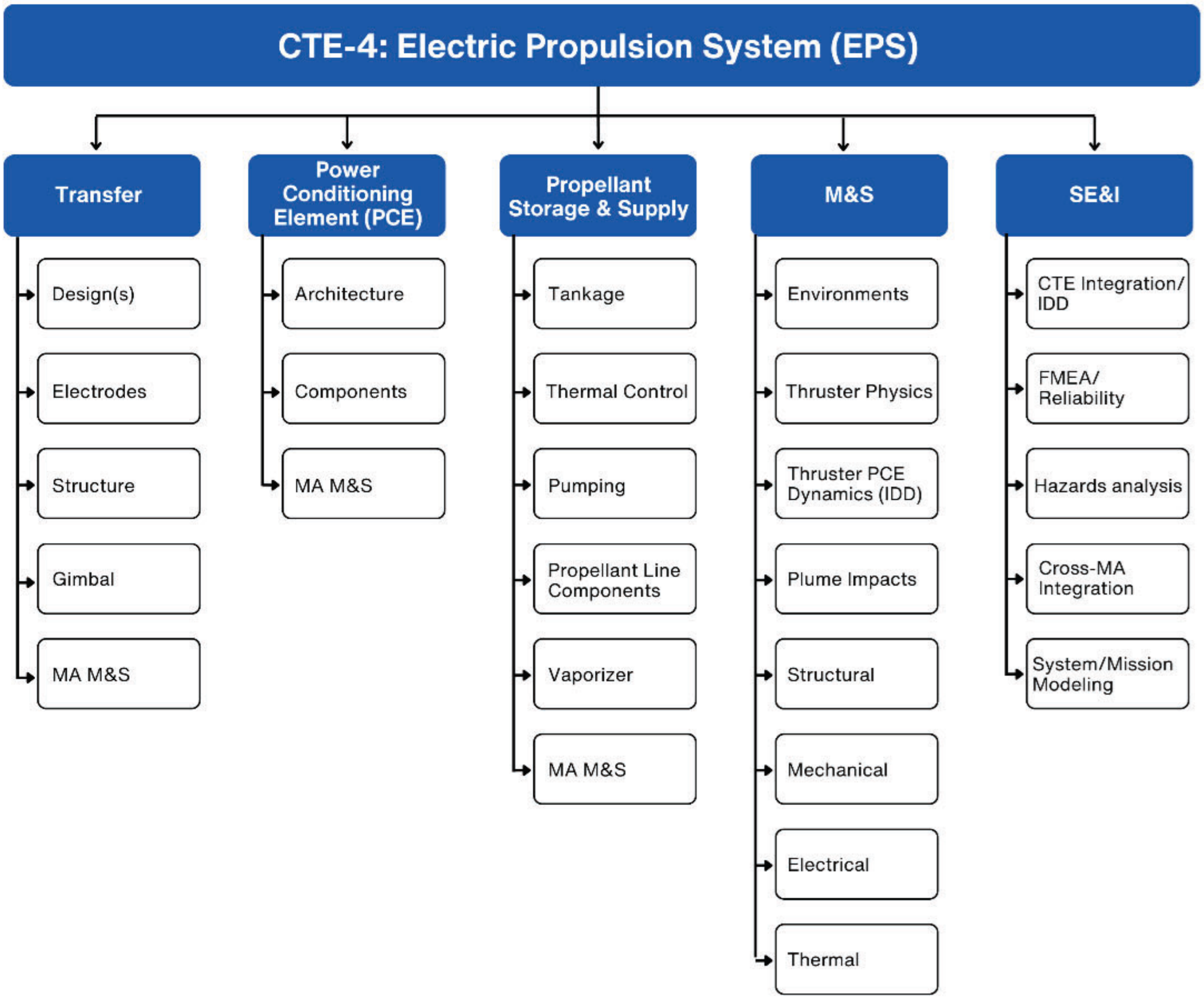


Figure 6.4: WBS for EPS Subsystem Development Management.

class power levels. There has been significant acceptance of Hall thrusters, and increasingly higher power level thrusters up to roughly 100 kW_e have been developed and tested over the last two decades (ref. [105]).

Research and development on Hall thrusters was initiated in both the former Soviet Union and the United States in the early 1960s (ref. [162]). While the U.S. chose to pursue gridded ion thruster development, Soviet efforts produced multiple Hall thrusters demonstrated at different institutions, with a first flight around 1970. Hall thruster technology was reintroduced in the U.S. at the end of the Cold War in part through Strategic Defense Initiative funding in the early- to mid-1990s. These resources culminated in the Russian Hall Electric Thruster Technology program led by NASA and based on the Russian Central Scientific Research Institute of Machine Building (TsIINIMash) sub-kW_e TAL D-55 Hall thruster shown in Figure 6.6. A D-55 was incorporated into the Naval Research Laboratory's Electric Propulsion Demonstration Module (EPDM) that was flown on National Reconnaissance Office's Space Technology Experimentation (STEx) spacecraft – the first western flight of a

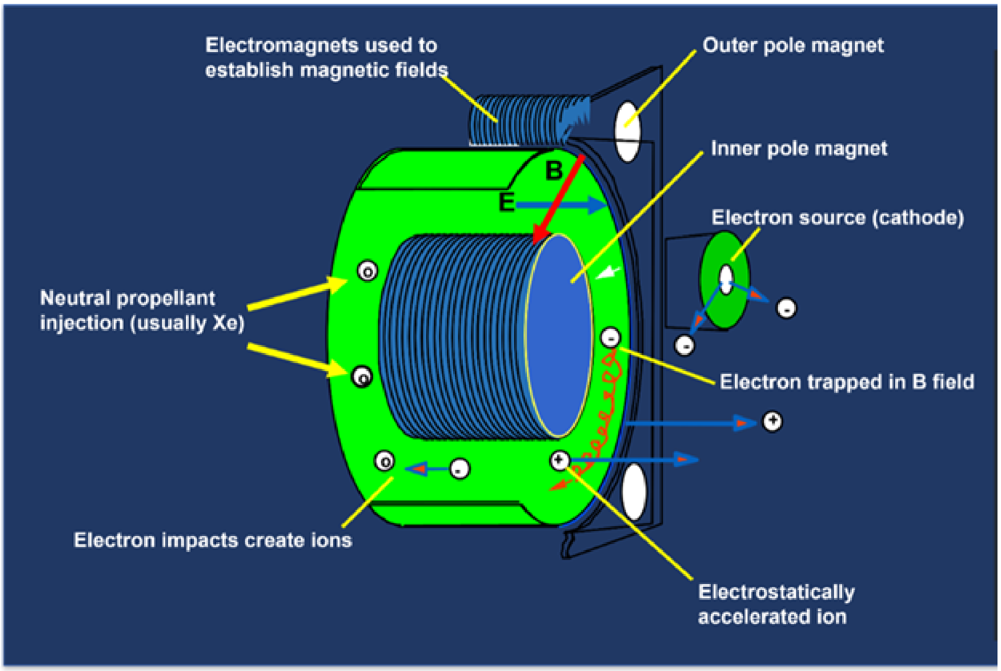


Figure 6.5: Hall Thruster Conceptual Operation Diagram.

Hall device (refs. [163, 164]).

Figure 6.6: Sub-kW$_e$ TsIINIMash TAL D-55.

Major Hall thruster system milestones include introduction of the 1.35 kW$_e$ stationary plasma thruster SPT-100 for NSSK through a joint venture between Space Systems/Loral and International Space Technologies, Inc. with Russia's Experimental Design Bureau Fakel (refs. [165, 166]), and the first interplanetary use of Hall thrusters on the European Small Missions for Advanced Research in Technology (SMART)-1 mission to the moon (refs. [167, 168, 169, 170]). These devices are shown in Figure 6.7.

At present, the use of Hall thrusters for spacecraft propulsion has been broadly accepted, including low power devices using krypton propellant on both the SpaceX Starlink and

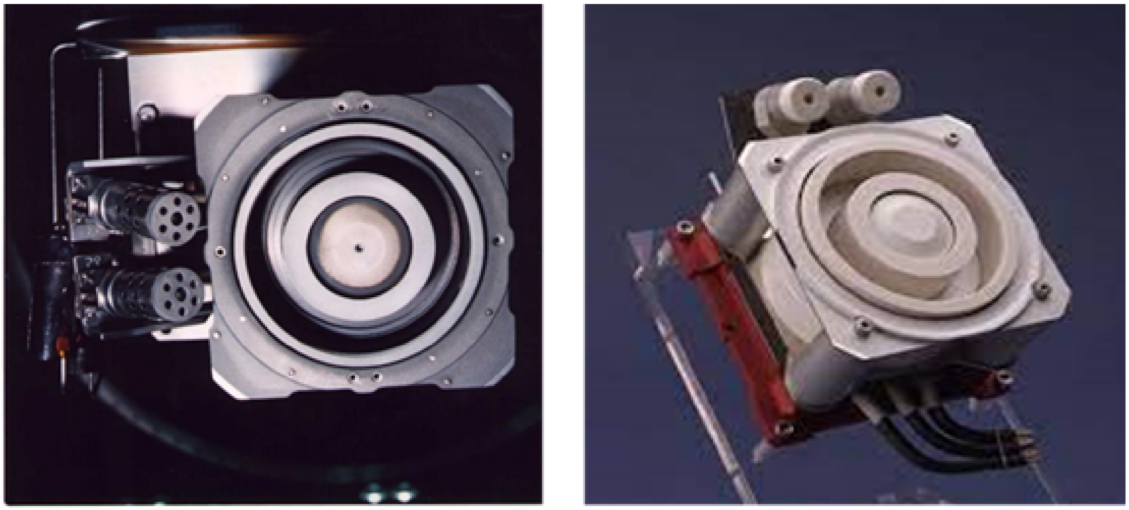


Figure 6.7: Fakel 1.35 kW_e SPT-100 Hall (left) and SMART-1 (right) Thrusters.

OneWeb satellite constellations (refs. [105, 171]). Every satellite prime contractor now offers kW_e-class Hall thruster options for orbit raising, station keeping, and de-orbit, leveraging the rapidly expanding U.S. and international industrial base for Hall thruster production. Over 1000 Hall thrusterpowered spacecraft are now successfully flying, providing significant confidence for kW_e-class systems. In fact, many of the sub-5 kW_e-class systems flown to date have demonstrated lifetimes of many thousands of hours as shown in Table 6.1.

Table 6.1: Demonstrated Hall Thruster Endurance for Typical Technology Examples. (Demonstrated endurance was not to end-of-life.)

Hall Thruster System	**Source**	**Power Level (kW_e)**	I_{sp} **(sec)**	**Demonstrated Lifetime (hours)**
SPT-100	Russia	1.35	1,500	>10,000 (ref. [166])
PPS-1350	France	1.35	1,500	>7,000 (refs. [168, 169, 170])
SPT-140	Russia	4.5	1,500-2,000	>10,000 (ref. [172])

The next evolutionary step for Xe-fed Hall thrusters came with the development of 4.5 kW_e-class devices for NSSK on the Air Force's AEHF GEO COMSAT constellation (ref. [173]). Initial AEHF Hall systems (designated the BPT-4000) were produced by the Aerojet Rocketdyne (AR). Several major design iterations have resulted in the present SOA flight XR-5 system (see Figure 6.8 from ref. [174]). The XR-5 has been tested to >10,000 hours and fully validated physics-based modelling projects thruster lifetimes of >20,000 hours. This thruster forms the basis for all modern "magnetically-shielded" Hall thruster designs (refs. [175, 176]). The combination of testing and modeling performed for XR-5 lifetime quantification will also be essential for lifetime projections of higher power devices. The long duration testing on the XR-5 demonstrated the profound benefits of the magnetic shielding concept, where careful shaping of the magnetic field directs the highenergy ions away from material surfaces in the thruster reducing wear and erosion to near-zero.

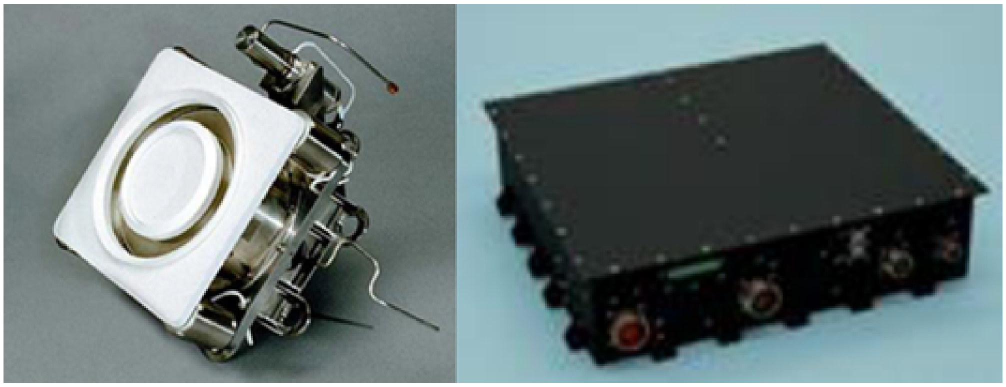


Figure 6.8: SOA XR-5 Hall Thruster and PPU.

In electric thruster testing, facilities effects generally refer to situations where the conditions in ground testing cannot be matched to those experienced during in-space operation due to the presence of or limitations imposed by the test facility. Facility effects are a major concern in Hall thruster operation (refs. [177, 178]), leading most recently to deviations between ground test measurements and in-flight operation during the first AEHF flight. In this flight, the AEHF apogee kick stage failed, and the BPT-4000 thrusters were used to complete orbit raising, saving the mission (ref. [179]). While this rescue in space was successful, unexpected behavior was observed at some operating points. Extensive modeling and test efforts were undertaken to address the observed discrepancies (unavailable here due to ITAR restrictions). The results of these investigations combined with the successful operation of Russian SPT-140-class technology, which operates at a similar power level and has been demonstrated in space (refs. [172, 180, 181]) provide reassurance that operational differences between ground and space are fairly well understood for 5 $\mathrm{kW_e}$-class thrusters. Additional flight data from NASA's Psyche mission, which uses the SPT-140 thruster, will be used to provide an additional point of comparison between ground testing and in-space operation. Extension to a cluster of thrusters operating in a 1 $\mathrm{MW_e}$ building block may not be straightforward, and the present plan assumes that extensive modeling and simulation efforts supported by sub-scale ground testing (cluster of up to six HERMeS-class 12.5 $\mathrm{kW_e}$ thrusters – built into this TMP) will be required to develop valid ground test protocols.

The thruster/PPU combination for the PPE of NASA's Lunar Gateway (refs. [144, 182, 183]) represents the next step in Hall system advancement. The PPE includes 6 $\mathrm{kW_e}$ Xe-fed BHT-6000 thrusters from Busek and 12.5 $\mathrm{kW_e}$ Xe-fed AEPS thrusters from Aerojet Rocketdyne. These thrusters are presently in the qualification phase (ref. [184]). The BHT-6000 operates at voltage set points of 300 and 600 V providing I_{sp} levels of approximately 2,000 and 2,700 s, respectively (ref. [185]). Significant early development of the 12.5 $\mathrm{kW_e}$-class Hall Effect Rocket with Magnetic Shielding (HERMeS) was performed for projects like NASA's Asteroid Rendezvous and Redirect Mission (refs. [186, 187, 188, 189, 190, 191, 192, 193, 194, 195]). The Aerojet Rocketdyne AEPS thruster system has six throttle points between 300 and 600 V for operation at power levels between 2.6 and 12 $\mathrm{kW_e}$ (refs. [196]).

A move to higher power Hall thruster testing (20+ kW_e) at NASA GRC was initiated in the late 1990s with a thruster obtained from TsIINIMash (designated the TM-50). Testing of the TM-50 was followed by the development and extensive investigation of the NASA-457M thruster, culminating with the NASA-457M v2 50 kW_e-class device tested in the 2010-2015 timeframe. In addition to operation at the nominal design power, this thruster was also operated for brief periods at 100 kW_e. Figure 6.9 shows pictures of the NASA-457M v2 up close and installed for testing in a large vacuum chamber at GRC (ref. [153]). At the rated 50 kW_e set point, the thruster operated at roughly 500 V with an I_{sp} near 2,500 s. It was noted at the time that 1) the maximum operating power level was limited by the ability of the barium oxide-infused hollow laboratory cathode to supply the required current levels for extended operating periods and 2) that development of longlife, high-current cathodes is required for further advancement. For a high-power (≥100 kWe) Hall thruster, long-life (≥25,000 hours) cathodes with a current capability on the order of 100 to 200 A are required. The required current level is based on the power per thruster and the thruster operating voltage.

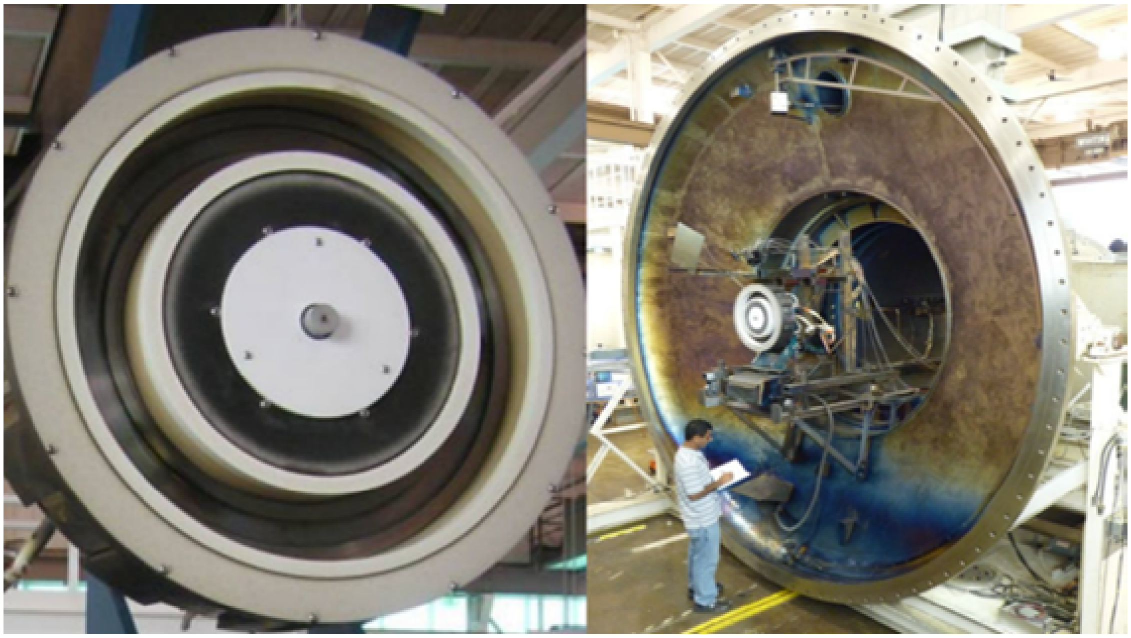


Figure 6.9: NASA-457 v2 50 kW_e-class Thruster.

While 100 kW_e thrusters have been proposed as the basic building block for high power Hall clusters, the final recommendation for power per thruster will be made based on SME analyses to be completed early in the first quarter of the maturation project (see ref. [197]). The optimal operating discharge voltage will be similarly selected. Based on SME projections to date, 100 kW_e and 600 V are projected as the lower bounds for these values. A 100 kW_e thruster operating at approximately 600 V would require a steady state cathode current in the 160-170 A range. At the other end of the spectrum, a 1 MW_e building block employing 3 Hall thrusters operating at 800 V would require cathodes with an operating capable of roughly 400 A. It is noted that recent advances in lanthanum hexaboride (LaB_6) cathodes (including heater-less devices) are the most likely choice for operation at these current levels (refs. [198, 199, 200]).

One test on a HERMeS-class 12.5 kW_e thruster indicated that LaB_6 cathodes can be operated with relatively high levels of oxygen (as an impurity) in the flow without degradation in performance or projected life (ref. [201]). This capability extended to NEP-class power levels would significantly reduce propellant purity concerns.

A high-power Hall thruster was also demonstrated in NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) program (refs. [147, 148]). This was a nested-channel thruster called the X-3 (also designated the XR-100) and designed to provide a wide power range up to 250 kW_e. The thruster, shown in Figure 6.10, was fabricated at the University of Michigan and tested using Aerojet Rocketdyne modular power processing technology. During the program, this device operated at steady state power levels between 50 and 100 kW_e. For the highest power cases in which thermal equilibrium was achieved (70 kW_e), the operating voltage was roughly 300 V with I_{sp} in the 1900–2000 s range.

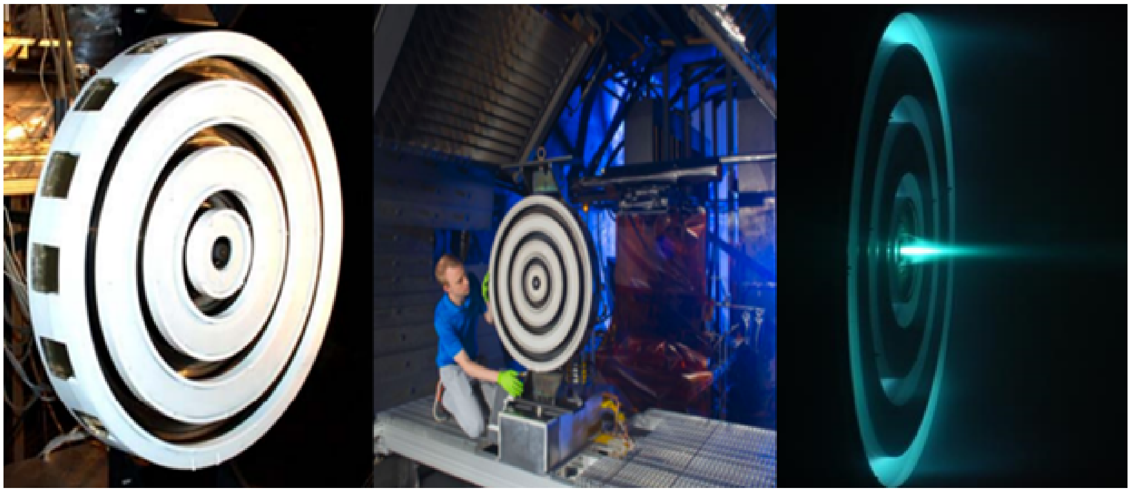


Figure 6.10: X-3 Hall Thruster from NASA's NextSTEP Project.

In the MTAS assessment examining human exploration of Mars in the 2039 timeframe (ref. [18]), the use of 100 kW_e-class Hall thrusters (based on NASA-457M thruster technology and scaling) was assumed as a baseline for a 1.8 MW_e propulsion system. For that study, two panels or clusters of ten 100 kW_e devices were used in a nine thruster plus one spare configuration to provide 1 MW_e per panel. An artist's conception of this system with sizing is shown in Figure 6.11. In the study, a single thruster mass of 250 kg (thruster only) was estimated, and it was assumed that thrust vector control was provided by gimballing the full panel.

As noted in the Introduction of this TMP, for a human Mars mission the power level and powerper- thruster are not yet defined. Thruster sizing with respect to mass and cost has been studied for relevant power levels (ref. [197]) and this will be revisited in an SME workshop at the start of the project. SNP-sponsored analysis to date suggests that for an opposition-class human Mars mission using a Hall-powered system, a total propulsion capability of 2 to 4 MW_e will be required (refs. [21, 22]), forming the rationale for the SNP modular development approach at the 1 MW_e-level. The MTAS thruster pod (ref. [18]) provides an excellent starting point for comparisons in the SNP-planned design and

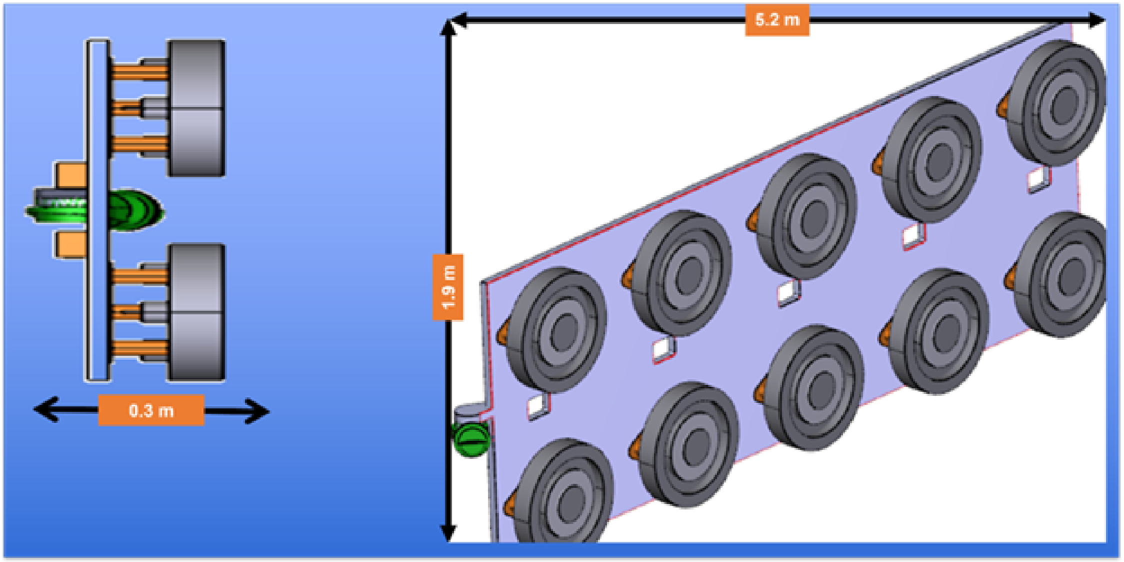


Figure 6.11: Artist Conceptions: MTAS Design for 1 MW_e Panel in Nine Thruster Plus One Spare (side view on left, skewed front view on right) (after ref. [18]).

development efforts described in this document.

Power Processing: A comprehensive study of power conditioning options for NEP was performed by Rockwell for NASA in 1993 (ref. [202]). While the study focused on ion and MPD thruster applications, the basic findings are applicable to Hall thruster systems. The study covered more than SNP's definition of power processing in CTE-4 (e.g., it included the isolating stepdown transformer that is included in CTE-3 of this TMP) and evaluated DC transmission and both high and low frequency AC transmission (at 60 Hz and 5 kHz). Excluding the transformer, the power conversion train included an AC-to-DC converter (switching rectifier followed by an output filter and a DC-to-DC converter and output filter to operate the thruster (primary acceleration power supply and other required functions). Two approaches are possible for Hall thruster power delivery and conditioning: 1) the conventional PPU approach using DC-DC converters as described by Rockwell, which are similar to those flown on all current and planned Hall thruster systems (e.g., NASA's PPE for Gateway and the Psyche mission, refs. [108, 203], respectively) or 2) direct application of power from the AC-to-DC converter. The power conditioning unit in the latter case is typically referred to as a Direct-Drive Unit (DDU) and is projected to reduce system complexity, reduce the need for high-power semiconductor components, and increase overall efficiency by driving down conversion losses. DDU definitions and configuration options vary across the community. For the development of this TMP, SNP defines a DDU as a unit in which the discharge voltage is derived from the PMAD input using a simple rectifier/filter stage that does not incorporate conventional DC-DC power converters for voltage step-up/step-down. It is noted that if DDU development efforts are unsuccessful, the DC-to-DC converter stage can be used with a reduction in efficiency and increase in mass (both within the bounds of the system mass and performance modelling and simulation tools developed by SNP). DDU and conventional PPU options will be discussed at the opening workshop and a recommendation on which option (or options) to carry for initial hardware maturation. In either case, an AC-to-DC converter will be required at the front end of the power conditioning system.

A highly simplified block diagram of the different power supplies needed for a conventional Hall thruster PPU is shown in Figure 6.12. The power must be conditioned to maintain the required current and voltage output characteristics to support thruster ignition, throttling (if necessary, particularly to manage thermal shock during start-up), steady-state operation, discharge transient management, and thruster shutdown. At the core of the PPU is the discharge supply. This supply controls the anode-to-cathode discharge, which generates the thrust and consumes about 90% of the power delivered to the thruster. The other supplies shown in the figure are for:

1. Magnet operations (a SOA single-channel device with two independently powered magnet coils is shown in Figure 6.12). Additional supplies may be needed for extra coils in a multichannel thruster such as the X-3,
2. A cathode heater to support thruster startup,
3. A cathode keeper supply to ignite the cathode and minimize cathode erosion from ion bombardment.

The negative poles of the discharge, heater, and keeper power supplies are common, while the magnet supply outputs are electrically isolated from the other power supplies.

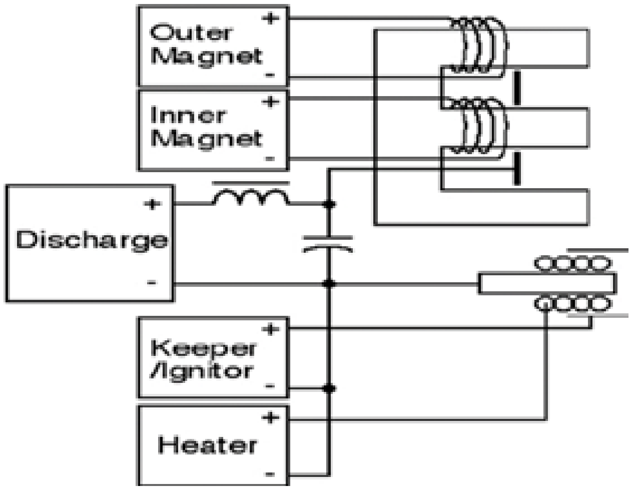


Figure 6.12: Simplified Electrical Block Diagram of Power Supply Required for Conventional Hall Thruster PPU.

It is possible that the cathode heater supply could be eliminated through the development of a heater-less cathode. Significant research and development efforts have addressed this possibility with LaB_6 cathodes for advanced applications (refs. [149, 150]). This would require appropriate power conditioning to manage heater-less ignitions and further development to determine the efficacy of the approach for the NEP application.

To date, all Hall thruster flight applications have been solar powered with PPU input voltages ranging from 24 to 150 V_{DC} (dependent of spacecraft bus characteristics). PPUs have typically used conventional converter topologies (e.g., H-bridge, Weinberg) to accept the input DC bus voltage and step it up to the required DC discharge voltage, with electrical taps from the input DC bus voltage to power the other supplies. The 12.5 kW_e AEPS Hall thruster system will use this conventional PPU approach, with the AEPS thrusters operating over six throttling set points at main discharge voltages of 300 and 600 V.

For high-power X-3 operation under the NextSTEP project, multiple lower power units were "ganged" together. A simplified block diagram of the X-3 PPU is shown in Figure 6.13. Here, seven identical Discharge Supply Units (DSU) are configured to independently power the individual rings of the thruster.

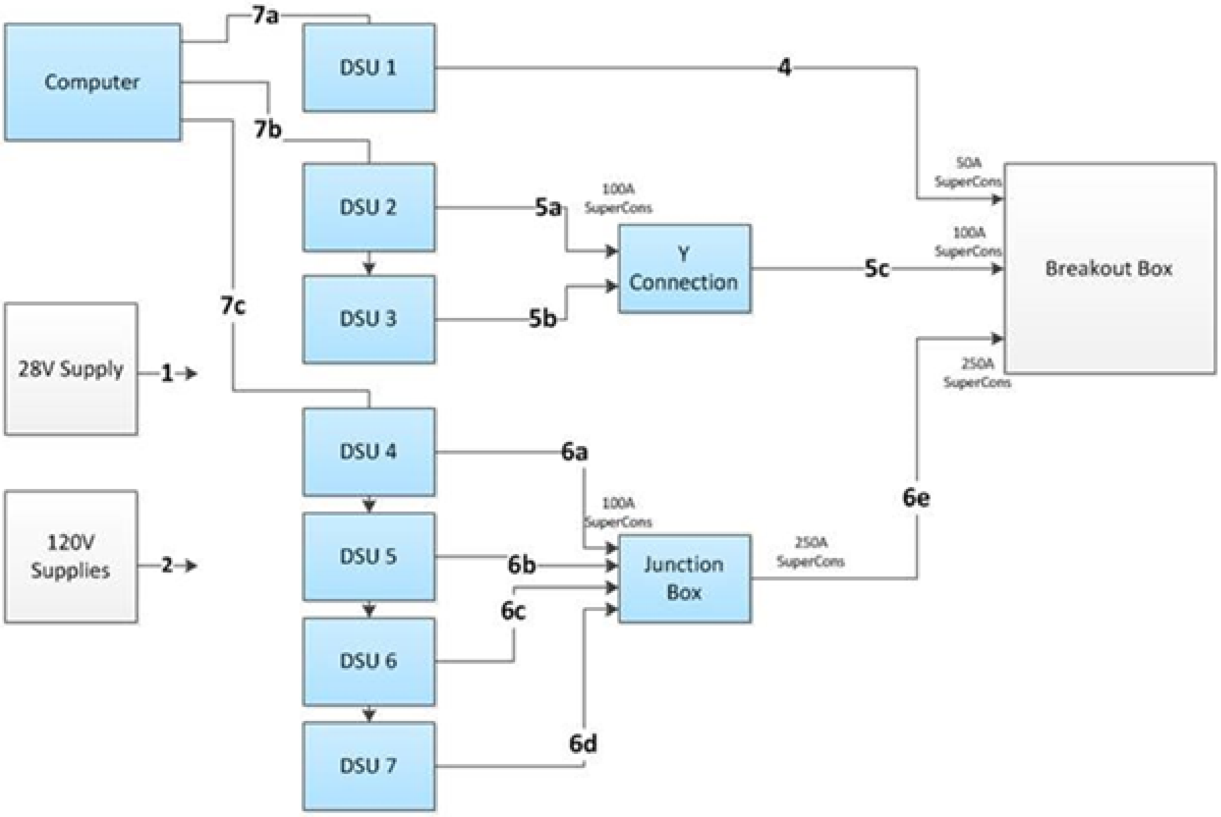


Figure 6.13: Simplified Electrical Block Diagram for X-3 PPU Used in NextSTEP Testing.

Conventional flight PPU systems operating from solar array-supplied DC power are highly optimized and operate at efficiencies in the range of 92 to 97% producing typical on-orbit discharge voltages between 300 to 400 V. Several ground test units, including the X-3 system operated at discharge voltages of 500 V or greater. By contrast, the NEP system must accept AC inputs (at frequencies presently estimated to be roughly 2 kHz) from the output of the CTE-3 PMAD transformers, with the expected discharge voltages expected to be between 600 and 1000 V_{DC}, which may necessitate an active AC-to-DC converter on the PMAD output.

Solar array-powered DC direct drive systems for Hall thruster operation were successfully operated at both GRC (refs. [204, 205]) and in the National Direct-Drive Testbed (NDDT) at the Jet Propulsion Laboratory (JPL) (refs. [206, 207]). In the most recent and relevant testing at JPL, two 6 kW$_e$-class H6 thrusters developed in a collaboration between JPL, the University of Michigan, and the Air Force Research Laboratory were tested in peak-power tracking experiments in the NDDT (ref. [151]). The physical hardware for these tests is shown in Figure 6.14 and a simplified circuit is shown in Figure 6.15.

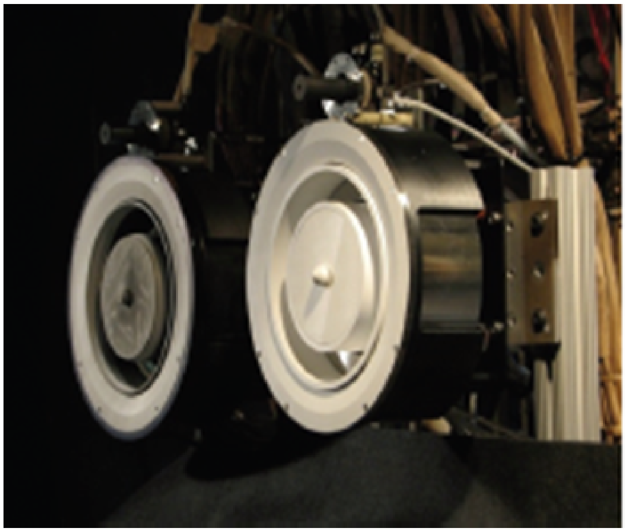


Figure 6.14: H6 Thrusters Mounted in NDDT for Solar-powered Direct-drive Testing.

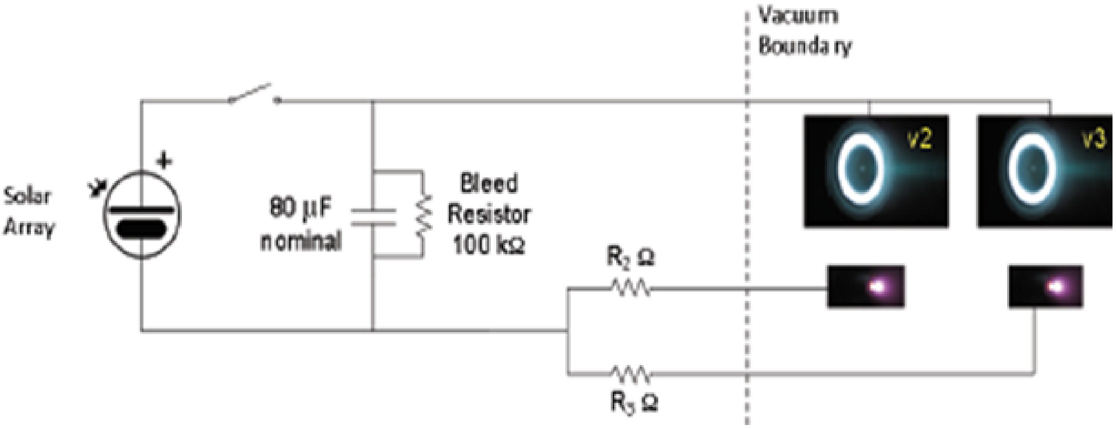


Figure 6.15: Simplified Electrical Block Diagram for Dual H6 Hall Thruster Direct-drive Testing.

The past work involved direct-drive using solar array-supplied DC power, making it not directly analogous to the situation for NEP where DDUs will need to accept high frequency AC power from CTE-3. However, that work did show the effectiveness of the DDU concept and, perhaps more importantly, demonstrated startup and steady-state operations of two thrusters operating simultaneously from the same power source at a combined power level of 10 kW$_e$. Electrical interactions and the required isolation between individual thrusters are major aspects of clustered Hall thruster systems. Clustered operation has been studied on low power devices (<300 W) (refs. [151, 208, 209]), but new in-depth research and development at representative high-power levels will be required for technology advancement in a $\mathrm{MW_e}$-class NEP system using multiple (3-10) thrusters in a cluster, with each operating at 100 $\mathrm{kW_e}$ or more.

High current transients (e.g., current flares, current spikes, or spark events) must also be accounted for in Hall thruster power processing design and testing. These spikes have mainly been ascribed to the shedding of carbon flakes that have accumulated on thruster surfaces due to backsputter from graphite targets used in ground testing, but they can also be due to redeposited erosion products from the thruster itself. An in-depth study of this phenomena was performed by Lobbia *et al.*, (ref. [210]) using a 6 $\mathrm{kW_e}$ magnetically-shielded thruster that was a sub-scale proxy of the 12.5 $\mathrm{kW_e}$-class HERMeS thruster (see, for example, refs. [186, 187]). In this research, current transients of over 300 A were observed and the implications of the findings are being evaluated for NASA's AEPS propulsion subsystem. At a minimum, these phenomena will increase harness and isolation requirements (i.e., adding mass) but to date, no major changes to power electronics have been required (ref. [211]). Starting transients and oscillations observed in HERMeS-class hardware (ref. [196]) must also be considered. There has been little research on these phenomena for high power NEP-class thrusters and significant focused research is anticipated as part of the CTE-4 development effort.

One specific technology that was discussed in the SNP-sponsored PMAD TIM (ref. [30]) was wide band gap (WBG) semiconductors. While research into WBG devices is ongoing, especially in NASA's electric airplane program (see, for example, refs. [212, 213]), discussions with SMEs indicate that the SOA for radiation-tolerant, high voltage, silicon carbide (SiC)-based WBG semiconductor technologies should be assessed as having a low TRL and high AD^2 such that they would likely not be available for near-term implementation in any PPU or DDU configuration. Based on these inputs, the availability of WBG technology is not assumed. That said, recent discussions with industry experts indicate that while SiC-based WBG devices are not feasible, gallium nitride (GaN)-based devices may have potential (ref. [134, 135]). EPC Space currently has commercial product lines that target the 300 V market and SME discussions indicate that there is no fundamental physical limit to going much higher (ref. [136]).The Hall discharge voltage requirement ($\sim$600 V) would necessitate a 1200 V rating to achieve the industry standard derating factor of 2. SME inputs indicate that there are no known physical barriers to development but that getting to this level would not be straightforward engineering and that a realistic development process may require an approach that steps up the voltage capability through a series of intermediate developments. The most recent developments in GaN WBG components will be reviewed at the opening workshop with an expected result of a recommendation to SNP on whether or not to pursue WBG technology as part of the path for power processing maturation.

A final major issue that will need addressed in the design and development of a high power PPU/DDU is the management of waste heat in the system. As the power levels grow, this becomes an every larger issue (5% resistive losses on an input power of 1 $\mathrm{MW_e}$ is 50 $\mathrm{kW_e}$), and the design of the power electronics (and indeed, of CTE-4 overall) will need to account for the rejection of this heat load. This issue is compounded by the presence of multiple thrusters (and a commensurate number of power processors) operating in close proximity, reducing the solid angle over which heat can be rejected without affecting neighboring units. The maturation plan includes the development and validation of a practical heat rejection strategy as part of individual thruster and multi-thruster testing campaigns.

Propellant Management and Storage: Although the logistical challenges associated with acquiring and handling the amount of Xe propellant required for a human Mars mission are daunting, these are not issues requiring significant technology maturation and investment at this point. Similarly, available Xe propellant flow management and delivery technologies will likely be easily scalable through straightforward engineering practices and are not addressed here. By contrast, Xe storage technology is a major issue associated with a Hall-based NEP system. In both the Deep Space 1 and Dawn missions, carbon fiber overwrapped titanium storage tanks were used for supercritical Xe storage (roughly 85 and 500 kg of Xe for the two missions, respectively) (refs. [214, 215]). Supercritical storage will also be used for the NASA Gateway PPE, with work already in progress to develop tanks scaled from previous systems (ref. [216]). A human-rated MWeclass Mars mission using Hall thrusters will require over 100 metric tons of Xe propellant. Both supercritical and cryogenic Xe storage options are under consideration. Cryogenic Xe storage has not previously been used on smaller-scale missions (even up to the size of PPE) in part due to the added mass, power, and complexity required to implement cryo-coolers on propellant tanks. However, at NEP scales with a nuclear power source, cryogenic storage might be a less risky and potentially less massive option compared to very large, very high pressure supercritical Xe storage tanks. As part of the present maturation plan, an early workshop is proposed to 1) decide on the storage method and 2) outline a plan for a practical storage system development program.

Hall Technology Requirements and Advantages: Advancements to date and projections for achievable future high-power, modular units make Hall technology one of the primary candidates for NEP applications. SNP mission modeling performed in conjunction with SME inputs to date has provided preliminary KPP shown in Table 6.2 as guiding requirements for Hall thruster development.

Table 6.2: KPP Guidance for Hall EPS Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Power per Thruster ($\mathrm{MW_e}$)	0.1-0.3		1 $\mathrm{MW_e}$ "building blocks" are key to overall technology maturation strategy – number of units to reach $\mathrm{MW_e}$ are to be determined through an initial SME workshop.
CTE-4 Hall α (per string in $\mathrm{kg/kW_e}$)	5	3	CTE-4 Hall α (per string in $\mathrm{kg/kW_e}$)
Thruster Performance	η and I_{sp} shown in Figure 2.1		Performance values based on experimental data obtained from SNP SMEs. Performance projection from SOA sufficient for mission closure – no research and development required for performance improvement. (Curve represents nominal expected performance from available data. Mission modeling assumes ±5% absolute uncertainty to estimate mission closure mass impact.)
PPU/DDU Efficiency (η in %)	95	97	PPU/DDU Efficiency (η in %)
Total thruster operating time (hours)	25,000	30,000	Operating time assumes an approximate 10,000 hr spiral time from low-Earth orbit (LEO) to near-rectilinear halo orbit (NRHO). Thruster lifetime requirements would be significantly reduced with direct injection to (or assembly in) NRHO.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for power electronics.

Key features/attributes of a Hall-based EPS include:

1. Reliable flight experience at low power – At more than 1000 operational low power thrusters, the number of Hall systems in space dwarfs all other EP systems by at least a factor of 10.

2. Proven evolutionary capability – From the initial U.S. application on the STEx spacecraft at less than 0.5 $\mathrm{kW_e}$, Hall technology has evolved to the current SOA (the XR-5 system at $\sim$5 $\mathrm{kW_e}$), with the 12.5 $\mathrm{kW_e}$ AEPS thrusters for NASA's Gateway PPE well into the qualification process (ref. [216]). Both the NASA-457v2 and the X-3 thrusters have demonstrated the ability to operate at power levels above 80 $\mathrm{kW_e}$ for short durations.

3. Propulsive performance – High-power Hall systems are expected to provide an I_{sp} range of 2000-3500 s at high power-levels with efficiencies between 50-60%. The thrust-to-power projected for high-power Hall systems provides benefits over alternatives, especially for high Δv applications.

4. Demonstrated life with extensive existing M&S capability validated at low power levels, demonstrated advances in magnetic shielding methodology, and demonstrated use for higher power systems using alternate materials for both the cathode and thruster channel wall.

5. Established manufacturing processes and suppliers for Hall thrusters – Multiple U.S. makers (e.g., Aerojet Rocketdyne and Busek) and international vendors are already capable of delivering turnkey lower-power Hall systems. The evolution from early $\mathrm{kW_e}$-class devices through the XR-5 to the current AEPS systems at Aerojet Rocketdyne demonstrates at low power levels the ability to evolve the thruster to a new mission application.

6. Potential for simple DDU-based power systems – The stable, high voltage operation of these thrusters is well-suited for the elimination of SOA DC-DC converter systems. DDU topologies that significantly reduce complexity and mass while eliminating the need for low TRL and high $\mathrm{AD^2}$ wide band gap semiconductor components have been demonstrated in simultaneous operation of multiple low-power thrusters using both simulated and actual DC solar power sources. The rectification and filtering required for matching the thruster with a 3-phase AC power input is expected to be a straightforward engineering challenge.

7. Standard propellant control technology is either fully demonstrated or in-process for systems up to the 50 $\mathrm{kW_e}$ (with multiple thrusters operating simultaneously) planned for NASA's Gateway PPE. Direct scalability to $\mathrm{MW_e}$ class systems is anticipated without the need for significant research and development.

Table 6.3 shows the major aspects/gaps in CTE-4 requiring focused Hall technology research and development and a brief description of the advancements needed to move $\mathrm{MW_e}$-class Hall thruster technology from its present readiness level to TRL 5 in year 4 of the project. While much progress has been made in component development (e.g., high-current cathodes) and testing (e.g., dual thruster operation in a DDU testbed) at power levels below 10 kW_e, many challenges lie ahead. One critical task is the development of a plan to address the issues surrounding ground testing and the correlation of ground test data to data from thrusters operating in space. The Xe propellant is not easily condensable and the facility effects involving the testing of clusters of high power thrusters represent large developmental uncertainties. While SNP does not anticipate the need for major "new" facilities, focused research and development, including both testing with appropriately scaled hardware and accompanying M&S, will be required to determine the appropriate test configurations and necessary upgrades to the pumping capabilities of existing large-scale facilities (for examples, VF-5 and VF-6 at NASA-GRC, the Space Power Facility at NASA's Armstrong Test Facility, and the Mark 1 Test Facility at Arnold Air Force Base).

Table 6.3: Major Hall Technology Aspects and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Thruster Testing in Relevant Environments	Demonstrate credible test capability for both individual thruster and cluster testing with validated models prior to a flight.
2	Thruster Sizing	System-level analysis to determine optimal power level per thruster/DDU string for MW_e-class cluster.
3	Clustered Operation including Transients.	Demonstrate stable, consistent operation of multiple thrusters in a relevant environment including both startup and long duration operation. This includes documentation and effective handling of both anticipated and anomalous transients. Develop the M&S capability required to credibly project endurance to the required (13,000+ hr) lifetime.
4	Cathode	Demonstrate long-endurance operation of a high-current cathode in a representative environment and the M&S capability required to credibly project to the required (13,000+ hr) lifetime at the required discharge current (plus margin).
5	Channel Design, Materials, and Electrical Configuration	Development and demonstration of a thruster with assembled body materials (e.g., monolithic channel or ring geometries using graphite or ceramic materials), geometry, and magnetic field configuration capable of meeting projected worst-case environments and long-term operation in hard vacuum. Develop the M&S capability required to credibly project to the required (13,000+ hr) lifetime.
6	DDU Design & Components	Development of a definitive architecture for the DDU, multiple (5-6) high-power thruster operation demonstration, and assurance that all components are available at the required qualification levels.

Table 6.3: Major Hall Technology Aspects and Advancement Requirements.

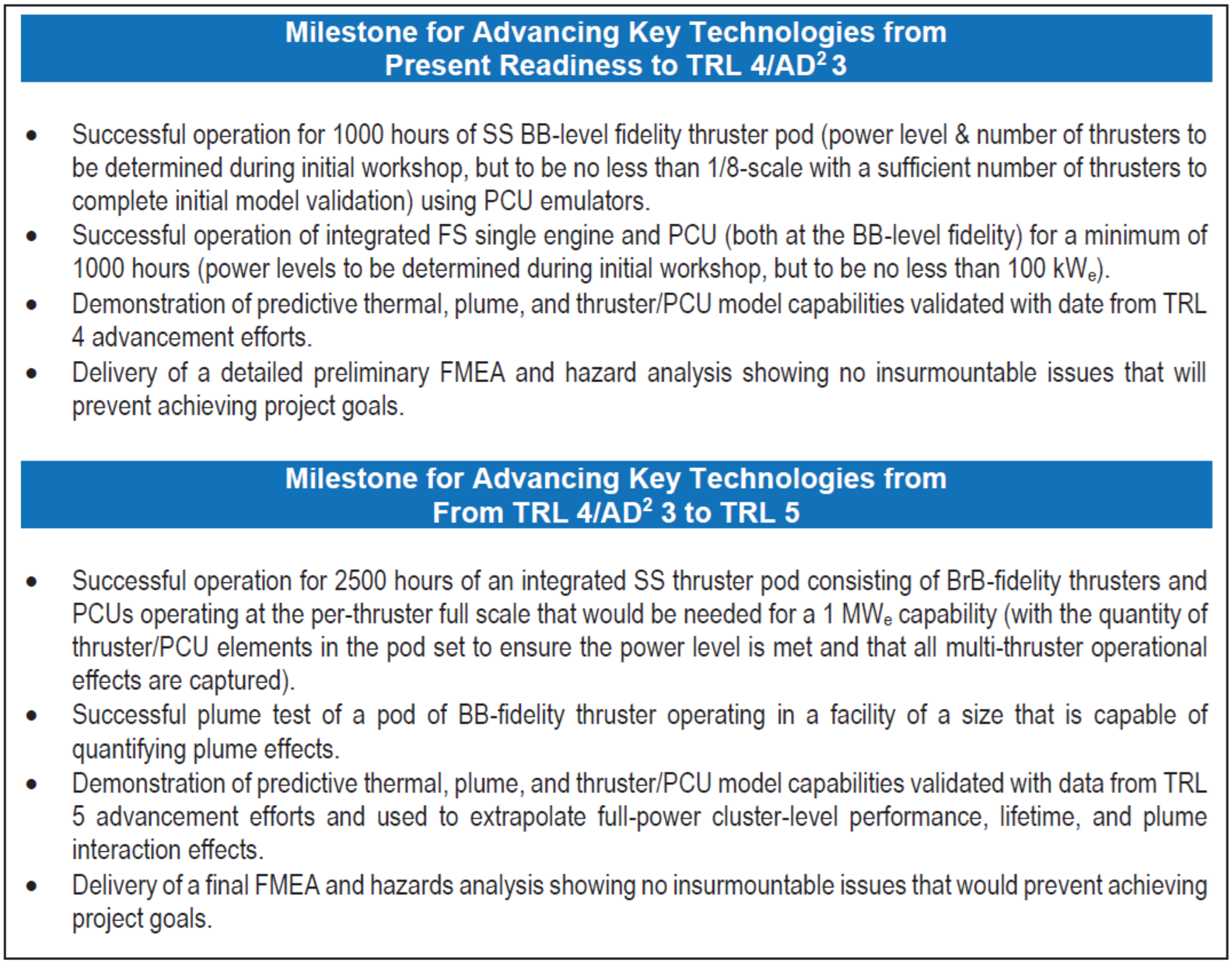
	Technology Description	**Advancement Descriptions**
7	Propellant Storage	Selection of Xe-propellant storage method (cryo versus supercritical) and demonstration of a BrB, 1/2-scale storage system with demonstration of M&S capability required for FS development.
8	Plume Impacts	Detailed models of both the thruster electrical characteristics and plume impacts for application to future spacecraft design efforts. Develop M&S capabilities required for projection to practical applications, validated using data from high-power thruster cluster testing in a large facility
9	Thruster System M&S	The thruster subsystem carries the TRL/AD^2 of the lowest aspect of the subsystem and early high-power (single and clustered) testing is problematic. Extensive efforts are required to develop and validate the M&S required to determine the effects of controllable parameters, project stable operation and required life, and capture characteristics required for future integration with other subsystems.
10	FMEA Development	Selection for advancement to TRL 6 at the end of the project depends not only on the successful completion of all testing and M&S projections but also on the ability to demonstrate that a reliable system can be assembled. For this, a comprehensive FMEA is required.

Operation in facilities beyond the current SOA combined with significant, validated M&S advancements are needed to convince SNP project leadership and the EP technical community that high-power Hall thruster test results are understood with respect to differences between groundbased and space-based operation. It is noted here that NASA STMD is funding the Joint AdvaNced PropUlsion InStitute (JANUS) in large part to develop an understanding of ground test capabilities and their relationship to space operations (ref. [217]). SNP will coordinate on plume research and development as practical and appropriate (ref. [218]).

6.2 Hall Technology Advancement Plans

The SNP project has developed a methodical approach to the advancement of high-power Hall technology from its present readiness level to the TRL 5 status. SNP-supported SMEs with technology development experience have reviewed Hall technology as it applies to a MWe-class NEP system and established the advancement goals outlined in Figure 6.16.

Table 6.4 and Table 6.5 provide a description of the major milestones with respect to advancement of the Hall thruster/PCU subsystem to TRL 4/AD^2 3 and then to TRL 5, respectively, and their relative timing (under the assumption that authority to proceed is given in Q1 of a fiscal year). Table 6.6 and Table 6.7 provide the anticipated milestones and timelines for propellant system maturation and facility development, respectively. The detailed schedules for this advancement are shown in Figure 6.17 with major milestones called out as for each subset of development.



**Milestone for Advancing Key Technologies from
Present Readiness to TRL 4/AD^2 3**

- Successful operation for 1000 hours of SS BB-level fidelity thruster pod (power level & number of thrusters to be determined during initial workshop, but to be no less than 1/8-scale with a sufficient number of thrusters to complete initial model validation) using PCU emulators.
- Successful operation of integrated FS single engine and PCU (both at the BB-level fidelity) for a minimum of 1000 hours (power levels to be determined during initial workshop, but to be no less than 100 kW_e).
- Demonstration of predictive thermal, plume, and thruster/PCU model capabilities validated with date from TRL 4 advancement efforts.
- Delivery of a detailed preliminary FMEA and hazard analysis showing no insurmountable issues that will prevent achieving project goals.

**Milestone for Advancing Key Technologies from
From TRL 4/AD^2 3 to TRL 5**

- Successful operation for 2500 hours of an integrated SS thruster pod consisting of BrB-fidelity thrusters and PCUs operating at the per-thruster full scale that would be needed for a 1 MW_e capability (with the quantity of thruster/PCU elements in the pod set to ensure the power level is met and that all multi-thruster operational effects are captured).
- Successful plume test of a pod of BB-fidelity thruster operating in a facility of a size that is capable of quantifying plume effects.
- Demonstration of predictive thermal, plume, and thruster/PCU model capabilities validated with data from TRL 5 advancement efforts and used to extrapolate full-power cluster-level performance, lifetime, and plume interaction effects.
- Delivery of a final FMEA and hazards analysis showing no insurmountable issues that would prevent achieving project goals.

Figure 6.16: Key Milestones in the EPS Hall Technology Advancement Strategy.

Table 6.4: Thruster/PCU Maturation Path - Present Status to TRL 4/AD^2 3.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
SME Workshops Thruster, PCU, M&S, FMEA	CTE4-1.1	Q1/Y1	SNP-selected SME panel review of existing Hall thruster/PCU technology to 1) select nominal thruster power-level for SS BB pod configuration, 2) evaluate component technology and set DDU design process, and 3) select design for pod configuration for SS testing. Preliminary risks and hazards lists generated (to be continuously reviewed and revised as necessary).
SS Thruster Module & FS PCU SME Design Review	CTE4-1.2	Q2/Y1	SME review of SS thruster pod power level & configuration and PCU design for BB testing with recommendation and SNP project selection. Specific SME emphasis on facility impacts/M&S advancement to maximize capabilities that will validate results.
SS Thruster Module & FS PCU Designs Complete	CTE4-1.3	Q3/Y1	SME review of the design for both the SS thruster & FS PCU for initial testing. Thruster emphasis on thruster cathode, material selections, and magnetic circuit design. PCU emphasis on component selection. Recommendations to SNP for approval.
M&S/FMEA Preliminary Drafts SME Review	CTE4-1.4	Q3/Y1	First draft of the planned step-by-step analysis of potential failure modes, impacts, and mitigation plans. First draft concentrates on potential failure scenarios in the planned Hall system test program and mitigation plans that can be rapidly implemented. Draft based on preliminary risk analysis chronicled in Section B.2. Concurrent M&S review to assure progress.
Initial IDD Draft Complete	CTE4-1.5	Q3/Y1	SME developed interface description document developed, reviewed, and delivered to SNP SE&I lead.
SS Thruster & PCU Hardware Delivered – SME Inspections	CTE4-1.6	Q1/Y2	SS BB thrusters delivered assembled as module. PCU units delivered and inspected. Hardware available for initial testing.
FS Thruster Final Design Review	CTE4-1.7	Q1/Y2	SME review of full-power thruster design with recommendation to SNP.
Plume Planning SME Review	CTE4-1.8	Q1/Y2	SME review of the TRL 4 plume test campaign with recommendations to SNP.
FS BB Test Plan Complete/SNP Review	CTE4-1.9	Q1/Y2	FS thruster test plans completed and approved by SNP.

Table 6.4: Thruster/PCU Maturation Path - Present Status to TRL 4/AD^2 3.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Pre-Test SS Thruster/PCU module SME Review	CTE4-1.10	Q2/Y2	SS thruster module installed in test chamber and integrated with external PCU emulators. Test plan vetted by SME's and approved by SNP. It is noted that environmental testing (e.g., vibration and thermal) will precede this step if recommended by SNP SMEs.
BB PCU Hardware SME Review	CTE4-1.11	Q2/Y2	SME review with recommendations with final approval from SNP.
SS TRR	CTE4-1.12	Q3/Y2	SNP review of SS test hardware installation and test plans – approval for SS testing.
Interim SME SS Test Review	CTE4-1.13	Q3/Y2	Review of early test results with recommendation for continuation (suggestions for modifications, if necessary).
SS Test Review/SNP	CTE4-1.14	Q1/Y3	SS testing complete. SNP-led SME review identifies and catalogs lessons-learned for FS testing and to support M&S advancement.
FS BB Hardware Delivery and Inspection/SNP	CTE4-1.15	Q1/Y3	SNP-led inspection of installed hardware and evaluation of readiness for FS testing.
FS Plume Test TRR/SNP	CTE4-1.16	Q1/Y3	SNP-led SME review/approval of plume test readiness.
FS BB Endurance TRR/SNP	CTE4-1.17	Q1/Y3	SNP-led SME review with approval for execution of shakedown testing prior to FS endurance testing.
Interim SME Plume and Endurance Test Reviews	CTE4-1.18	Q2/Y3	SME review of ongoing plume testing and shakedown testing results prior to FS endurance testing – recommendation for continuance – full plume and endurance testing proceed from this milestone to completion.
FS Plume Test Complete	CTE4-1.19	Q3/Y3	Plume testing complete – data package available for M&S validation/update.
Updated M&S/FMEA Draft Review/SME	CTE4-1.20	Q4/Y3	SME review of the updated FMEA and technical models (e.g., thruster/PCU electrical, thermal) and to determine that the planned plume and endurance testing will produce the data required for model validation and advancement (pre-test).
FS BB Test Complete	CTE4-1.21	Q4/Y3	1000-hour FS BB single thruster/PCU test completed – SME review of results with recommendations for BrB phase. Project report to NAR panel for pre-NAR assessment.

Table 6.4: Thruster/PCU Maturation Path - Present Status to TRL 4/AD^2 3.

Major Technology Milestones to TRL 4	#	**Timeframe (End Date)**	**Significance**
TRL-4 IDD and Risk & Hazards Lists Complete	CTE4-1.22	Q4/Y3	Initial IDD revised as necessary for BrB emulator development – delivered to SNP SE&I lead. Revisions to risk and hazards lists complete and delivered to SNP.
TRL 4 NAR (BB, M&S, FMEA)	CTE4-1.23	Q4/Y3	NAR advancement of CTE-4 Hall technology to TRL 4.

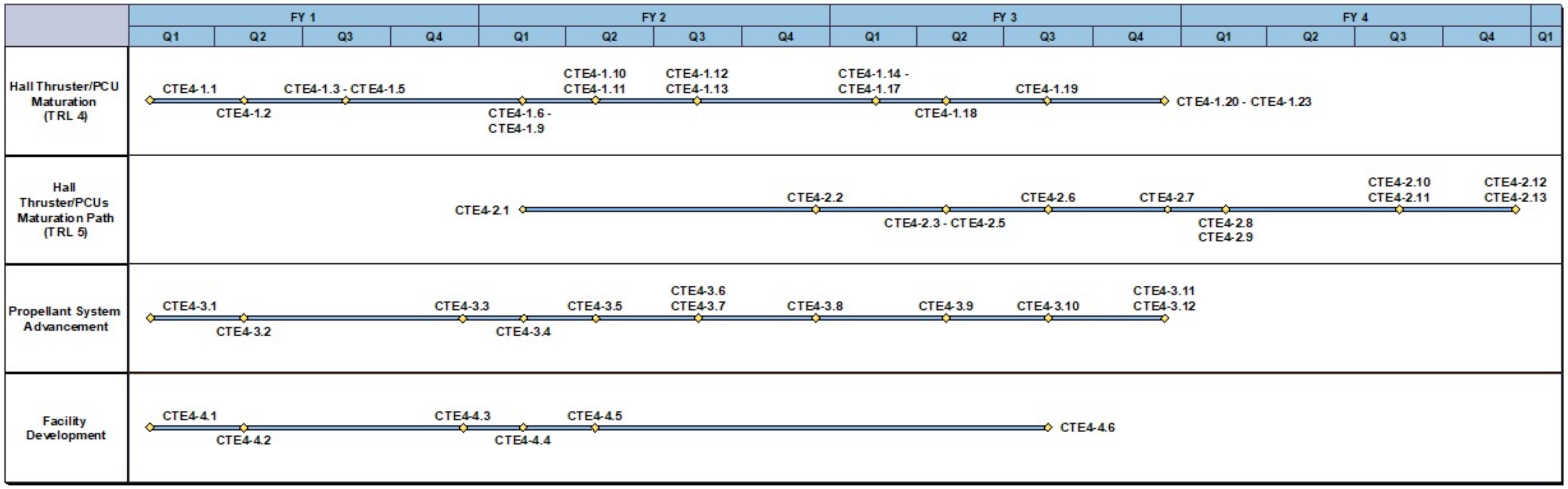


Figure 6.17: CTE 4 Hall Thruster Advancement Schedule.

Table 6.5: Thruster/PCU Maturation Path - TRL 4/AD^2 3 to TRL 5.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Preliminary BrB Design Workshop	CTE4-2.1	Q1/Y2	SME-led review of BrB designs (thruster and PCU) to assure the availability of all key required components. Hazard and risk lists reviewed and updated as necessary.
BrB Design Complete	CTE4-2.2	Q4/Y2	SNP approval of BrB designs for procurement - actions taken to assure timely delivery of all (thruster/PCU) components.
BrB Hardware Delivered/Test Plan Review (Inc Plume)	CTE4-2.3	Q2/Y3	BrB hardware delivered/assembled/installed prior to TRL 5 endurance and plume testing. SME review of hardware and test plans with recommendations to SNP.
FS BrB Plume TRR	CTE4-2.4	Q2/Y3	SNP-led SME review/approval of readiness for plume test on a FS thruster. SNP approval for test initiation.
BrB Endurance TRR	CTE4-2.5	Q2/Y3	SNP-led SME review/approval of readiness for endurance test. SNP approval for test initiation.
Interim M&S/FMEA Review	CTE4-2.6	Q3/Y3	SNP review to evaluate progress of all M&S efforts – tasks completed so data from both the BB endurance test and the large-scale BB plume test are available for comparisons to model predictions (thruster physics, thermal, plume, etc.). Comparisons will be evaluated with recommendations for additional modeling actions and any needed modifications. FMEA updated with SME review and recommendations for finalization.
BrB Testing Interim Reviews	CTE4-2.7	Q4/Y3	Concurrent review of early results from both plume and endurance testing – SME recommendation for continuation (with modifications, if necessary).
BrB Plume Test Complete	CTE4-2.8	Q1/Y4	FS plume testing completed with test results compiled and submitted for as inputs to M&S model updating and validation activities.
Plume M&S Review	CTE4-2.9	Q1/Y4	SME evaluation of plume M&S progress for validation and lessons learned. Recommendation for extended testing, if required.
BrB Test Complete	CTE4-2.10	Q3/Y4	2,500-hour BrB test completed – SME review of results with report to NA panel for pre-NAR assessment.
M&S/FMEA Drafts Submitted	CTE4-2.11	Q3/Y4	Final drafts of M&S and FMEA documents submitted for pre-NAR evaluation.
TRL 5 NAR	CTE4-2.12	Q4/Y4	NAR for advancement of CTE-4 Hall technology to TRL 5.

Table 6.5: Thruster/PCU Maturation Path - TRL 4/AD^2 3 to TRL 5.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Final IDD and Risk & Hazards Lists Complete	CTE4-2.13	Q4/Y4	IDD revised as necessary based upon BrB emulator development – delivered to SNP SE&I lead. Revisions to risk and hazards lists complete and delivered to SNP.

Table 6.6: Propellant System Advancement Schedule.

Major Milestones	**#**	**Timeframe (End Date)**	**Significance**
Propellant System SME Design Workshop	CTE4-3.1	Q1/Y1	Workshop report to evaluate all available information and recommend storage strategy (cryogenic versus supercritical) to SNP. Evaluation of propellant delivery system component status (with inputs from Gateway/PPE) to recommend focused research and development, if required.
BB System Requirements Complete with SME Review	CTE4-3.2	Q2/Y1	SME review of propellant system design and testing requirements (tank, delivery system, test demo). Note that this review includes an assessment of the minimum tank size required for TRL 4 and TRL 5 evaluation testing.
BB System & Preliminary BrB System Design Review	CTE4-3.3	Q4/Y1	SME review of the completed BB system design and a preliminary design of the proposed BrB system – results presented to SNP for full approval to finalize acquisitions and installation planning.
BrB System Design NAR	CTE4-3.4	Q1/Y2	BrB system design is complete and independently reviewed – key decision on size/configuration of storage hardware required for TRL 5 testing.
Xe Propellant & BB Components Delivered	CTE4-3.5	Q2/Y2	Xe and all components required for BB testing delivered and inspected by SME team.
BB Propellant System IOC	CTE4-3.6	Q3/Y2	SNP review of installed BB system – operational readiness confirmed.
BrB Tank Progress Review	CTE4-3.7	Q3/Y2	SME BrB propellant storage development progress – recommendations to SNP for continuance (with changes, if required).
BrB Propellant System Reqs Definition Complete	CTE4-3.8	Q4/Y2	SME review of all test requirements for plume & endurance testing – assessment of ongoing hardware and plans with recommendations to SNP.

Table 6.6: Propellant System Advancement Schedule.

Major Milestones	**#**	**Timeframe (End Date)**	**Significance**
BrB Propellant System Delivered/IOC	CTE4-3.9	Q2/Y3	BrB hardware delivered and installed, SME evaluation report/recommendations to SNP.
BrB Propellant System TRR	CTE4-3.10	Q3/Y3	SNP review of BrB propellant system – approval for testing.
Interim Propellant System Review	CTE4-3.11	Q4/Y3	SME review of ongoing FS BrB propellant system review with report/recommendations to SNP.
Final Propellant System NAR	CTE4-3.12	Q4/Y3	Independent review to assure propellant system hardware has attained TRL 5.

Table 6.7: Facility Development Schedule with Milestones.

Major Milestones	**#**	**Timeframe (End Date)**	**Significance**
Facility Workshop	CTE4-4.1	Q1/Y1	Workshop to review and reconcile past discrepancies between ground testing and inspace leading to development of preliminary facility requirements for TRL 4 and TRL 5 testing. Identification of potentially available facilities initiated with instructions to develop detailed upgrade requirements for leading facility candidates.
Requirements for TRL 4 Testing Facilities Complete	CTE4-4.2	Q2/Y1	SME review of facility requirements for TRL 4 testing – facility selection by SNP.
TRL 5 Facilities Reqs Complete/SNP Selection	CTE4-4.3	Q4/Y1	SME review of facility requirements for TRL 5 testing – facility selection by SNP.
TRL 4 Facilities IOC	CTE4-4.4	Q1/Y2	SNP review of upgraded TRL 4 test facilities complete – operational readiness confirmed.
TRL 5 Facilities Interim Review/SNP	CTE4-4.5	Q2/Y2	SNP-led SME review of TRL 5 facility upgrade plan and progress. Lessons learned from TRL 4 development and external inputs applied and modifications made if required.
TRL 5 Facilities IOC	CTE4-4.6	Q2/Y3	SNP review of upgraded test facilities complete – operational readiness confirmed.

Summarizing, the maturation plan progresses through a series of tests at increasing power level, hardware fidelity, and subsystem-level integration. The testing performed contains the following major steps to include:

- Initial sub-scale (SS) thruster testing with a pod of multiple thrusters (minimum 6 to ensure representative plasma, thermal and field characteristics) operating simultaneously to demonstrate stability and quantify plume interactions as well as provide data for model validation. The required thruster design, power level per thruster, and pod configuration including number of thrusters will be finalized at the SS Design Review. Laboratory PCU (either PPU or DDU) emulators will be used along with a BB propellant delivery system assembled using commercial off-the-shelf (COTS) Xe flow system components (including propellant tank).

- Testing with a BB-fidelity single thruster/PCU sub-system at the single-thruster power level chosen as the FS design target at the FS Thruster/PCU Design Review. The work will demonstrate that designs meet anticipated structural and thermal loads and provide required endurance and fault-tolerance. The extent of environmental testing (e.g., vibration and thermal) will determined by SME review of modeling data and "as built" hardware evaluations. The PCU will incorporate BB-fidelity components that demonstrate key functionalities (e.g., ignition, transient response, controlled shutdown, temperature, voltage range) required for flight.

- Testing with a BrB-fidelity thruster/PCU at a power level no less than 100 kW_e in a facility that provides test conditions to provide confidence in the acquired data with respect to the applicability of those data to operation in space. The system is operated for a minimum of 2,500 hours. M&S capabilities are advanced using data from all previous test to permit the identification of important physical phenomena and controlling parameters in the propulsion system and to allow for model predictions of the required lifetime for a long-duration mission (with margin).

- Large-scale plume testing of a thruster pod with at least BB-fidelity hardware in a large facility to provide data regarding thruster plume-to-plume interactions, electrical transients on startup and during nominal and off-nominal operation, and ion distributions within the plume mapping to validate M&S capabilities for mitigation of plume/spacecraft interaction issues.

All testing will be backed by M&S and a FMEA, and both will leverage test data to improve the fidelity and increase the range of applicability of the models and analyses.

6.3 CTE-4 Hall Technology Advancement Risks

The SNP project has performed a preliminary development risk assessment for Hall system advancement. As the project advances, extensive efforts will be focused on the development of a formal FMEA, the results of which will be documented as part of the overall Hall technology development efforts. Table 6.8 shows the 'Top 5' technical risks identified by

SNP SMEs. As shown in the table, all risks will be fully described with risk assessments using NASA's standard risk scale for consequence and likelihood (ref. [219]). Figure 6.18 presents these in the standard NASA risk matrix format.

Table 6.8: 'Top 5' EPS Hall Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total) (*Note: Each test in the long-duration testing sequences includes at least twice the test time necessary to successfully complete a test.)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
Hall-1	Ground test validity verification	Inability to credibly project performance and plume data obtained in ground testing to space application.	T	3	3	9	Early and continuing interactions with Gateway/PPE and STMD-funded Joint Advanced Propulsion Institute (JANUS) programs to evaluate experimental and M&S findings and implement "best known" test practices into TRL 4 and TRL 5 test sequences. Perform TRL 5 cluster testing in large-scale test facility equipped with > 100X better pumping capability than currently available. Apply all relevant lessons learned from AEHF program with respect to thruster design and facility grounding/shielding. Fully funded schedule reserve for test iterations with facility modifications in each test sequence.*

Table 6.8: 'Top 5' EPS Hall Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total) (*Note: Each test in the long-duration testing sequences includes at least twice the test time necessary to successfully complete a test.)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
Hall-2	Clustered thruster operation	Thruster plume interactions cause unacceptable operating characteristics at 500 $\mathrm{kW_e}$ to 1 $\mathrm{MW_e}$ module level.	T	3	3	9	TRL 4 testing of a SS thruster pod (using existing 12.5 $\mathrm{kW_e}$ PPE thruster design) with thruster number and configuration determined by SNP and external SMEs. Early SME review and recommendations followed by thruster testing of at least 2 FS thrusters in the BB plume test phase. Early TRL 5 testing of full-power thrusters in an SME-defined pod arrangement determined by SMEs after a review of all lessons learned from TRL 4 testing and any available JANUS and Gateway/PPE results. Fully funded schedule reserve for test iterations with thruster and facility modifications in each test sequence.*

Table 6.8: ‘Top 5’ EPS Hall Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total) (*Note: Each test in the long-duration testing sequences includes at least twice the test time necessary to successfully complete a test.)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
Hall-3	Cathode life	Cathode technology demonstrations insufficient to project required lifetime	T	3	3	9	Application of SME-recommended cathode technology option (LaB_6 or conventional BaO hollow cathode) immediately following Q1/Y1 technology workshop. Early emphasis on evaluation of cathode degradation in TRL 4 testing and M&S. Concurrent development of alternate technology based on option not selected with target of infusion by Q3/Y2. Fully funded schedule reserve for design improvements (if required) in all phases testing.*

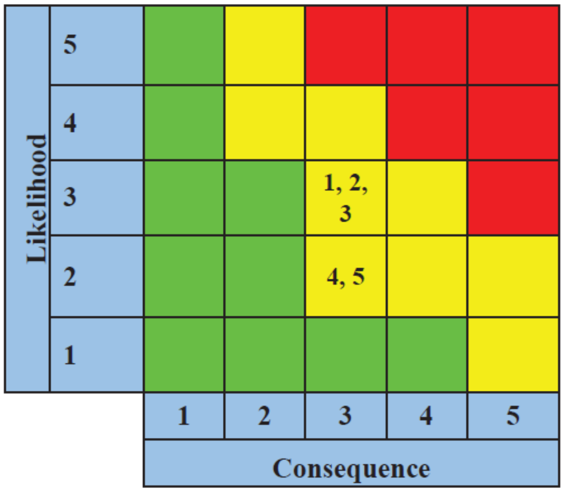
Table 6.8: ‘Top 5’ EPS Hall Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total) (*Note: Each test in the long-duration testing sequences includes at least twice the test time necessary to successfully complete a test.)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
Hall-4	Thruster fabrication	Inability to fabricate a 100+ kW_e unit that will meet launch load requirements and successfully operate in the required thermal environment.	T	2	3	6	Implementation of SME-recommended thruster channel material option (boron nitride (BN) or graphite) immediately following Q1/Y1 technology workshop. Early vibration testing with requirement that all testing (TRL 4 and TRL 5) involving FS thrusters be performed using at least one thruster that has been screened by going through the vibration test sequence recommended by SNP SMEs. Continuing dynamic structural M&S with the objective of producing an alternate design for implementation prior to TRL 5 testing. Fully funded schedule reserve for alternate design insertion prior to Q1/Y3.*

Table 6.8: ‘Top 5’ EPS Hall Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total) (*Note: Each test in the long-duration testing sequences includes at least twice the test time necessary to successfully complete a test.)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment** L	C	T	**Mitigation Strategies**
Hall-5	Xe storage system	Inability to design, manufacture and test a Xe storage system capable of meeting projected mass and safety requirements.	T	2	3	6	Q1/Y1 decision on cryogenic storage (CS) versus super-critical storage (SCS) of Xe propellant based on SME recommendations and evaluation of Gateway/PPE (SCS) progress compared to adaptability of known cryogenic storage technology. Concurrent development of alternate technology based on option not selected with goal of implementation capability prior to Q2/Y3. Fully funded schedule reserve for alternate design insertion prior to Q1/Y3.*

Risk Hall-1: There are very little data regarding high-power thruster plumes – testing to date has been limited to the 50 to 100 kW$_e$ range in two separate test campaigns. In one, a single channel Hall thruster rated at 50 kW$_e$ was tested briefly at power levels up to 100 kW$_e$. This testing focused mainly on performance and the operational envelope, and no plume measurements were published. In the other, a three-channel device was tested at power levels between 50 and 100 kW$_e$ under NASA’s NextSTEP program (see Figures 6.10 and 6.13 and accompanying description). In this testing, emphasis was placed on endurance and performance, not plume quantification. Some research and development on clustered thruster operation has been performed. Examples include research and development on low power plume interactions, performance, and cathode configuration using four sub-kW$_e$-class thrusters and a dual thruster (10 kW$_e$ total) test of a solar-powered DDU at JPL. There has been no testing of multiple closely spaced thrusters at high-power, and this will be a major area of focused research and development. The impacts of facilities on operational characteristics and the validity of ground testing are both major concerns. The SNP plan



Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨 1, 2, 3	🟨	🟥
2	🟩	🟩	🟨 4, 5	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5
	Consequence				

Figure 6.18: EPS Hall Thruster 'Top 5' Risk Ranking Likelihood and Consequence Span.

addresses this using existing or expected future data from in-space Hall thruster operations and through a series of additional tests at ever increasing power levels in large, existing vacuum facilities backed by an extensive M&S program designed specifically to evaluate and estimate facility effects. As noted above, these efforts will interface with the ongoing STMD-funded JANUS project (ref. [217]) to the greatest extent possible.

Risk Hall-2: While the successful test of two Hall thrusters (10 $\mathrm{kW_e}$ total) operated in close proximity with a solar powered DDU provides confidence that low-power Hall thrusters can be operated in tandem with minimal deleterious plume interactions, the operation of a $\mathrm{MW_e}$-class system with up to 10 thrusters in simultaneous operation is well-beyond SOA experience and represents the second major risk identified in the TMP development process. The present plan addresses this issue with a series of tests of increasing fidelity including,

1. A cluster of more than 2 SS thrusters (actual number to be recommended by SMEs). Option to leverage existing 12.5 $\mathrm{kW_e}$ thrusters developed for testing under the NASA Gateway program,
2. Large-scale plume testing at 100 $\mathrm{kW_e}$ in the TRL 4 advancement phase, and
3. Large scale cluster testing at total cluster power levels of 500 $\mathrm{kW_e}$ or greater in the TRL 5 phase.

All tests will be designed to support an extensive modeling and simulation effort to assess steady state operation as well as planned and anomalous transient events. Efforts will also leverage results from the ongoing STMD-funded JANUS program to the greatest extent possible.

Risk Hall-3: Cathode lifetime was identified as a major concern based on the importance to thruster health of efficient, stable, long-term emission. Most past and current SOA Hall (and ion) thrusters have employed hollow cathodes with inserts impregnated with low work function materials to support high-efficiency electron production at sustainable temperatures. The 50-100 $\mathrm{kW_e}$ testing at GRC employed a "laboratory-class" version of this technology with the caveat that research and development would be required to develop a flight-qualifiable version for those power levels. Multiple recent tests with LaB_6 cathode technology, including testing up to 100 kW_e in the NextSTEP program and testing with contaminated Xe, are encouraging and provide a very credible alternative. There are essentially no data on thruster cathodes that can meet an operational requirement of 100+ kW_e for $\geq$10,000 hours. To address this, a cathode technology will be selected as the primary candidate for focused research and development at the initial SME workshop (Q1/Y1), with a second carried as a backup for use in the thruster prior to TRL 5 testing if the primary cathode option does not meet required performance criteria.

Risk Hall-4: The Hall thrusters shown in Figures 6.9 and 6.10 (pictured with people for relative scale) are representative in size to those projected for flight. These thrusters are between a half-meter and a meter in diameter and have an estimated mass of roughly 250 kg. Boron nitride (BN) has been the material of choice for the channel wall of essentially all conventional SPT-type Hall thrusters. While this is an option up to 100 kW_e for single channel devices, the material blank required to fabricate larger channels from a single piece of BN is at or beyond the limit of current manufacturing capability. Manufacturing the thruster from multiple smaller pieces as was done with the X3 under NextSTEP is possible but structural integrity with respect to vibration tolerance, electrical insulation, and voltage holdoff are unproven. More recently, graphite-channel magnetically shielded devices have been successfully tested at power levels up to 10 kW_e and this material provides a more readily available, less expensive, and more easily machinable alternative. As with the high-power cathodes, a primary selection for thruster design (materials, number of channels, etc.) will be recommended by the SNP SME team at the opening workshop and at least one alternative will be carried for insertion prior to TRL 5 testing if necessary.

Risk Hall-5: Xe propellant storage is a major area of risk simply based on the lack of any experience with the quantity of Xe required for the subject mission (> 100 metric tons (MT)). Supercritical storage in composite-overwrapped pressure vessels (COPV) is the SOA. These tanks are used in all commercial systems, with single propellant tanks used in both Deep Space-1 ($\sim$85 kg of Xe) and Dawn ($\sim$500 kg of Xe). The Dawn tank development, while eventually successful, was problematic with the original flight tank and flight spare both failing under hydrostatic testing and requiring a tank redesign effort. COPV technology was selected for the Gateway program and large ($\sim$1,000-2,000 kg of Xe) tanks are currently under development. The realistic upper limit of supercritical storage is unknown. Cryogenic storage has been considered and published research indicates that this option can provide mass and volumetric advantages as the amount of Xe needed increases beyond Gateway's requirements. Existing cryogenic storage technology is scalable and similar to that being developed for other light cryogens (e.g., oxygen, O_2, and methane, CH_4). Both alternatives will be reviewed at the opening workshop with recommendations for both primary and backup development paths.

6.4 Hall Maturation Summary

Hall thrusters have a long history of successful operation in a variety of applications ranging from station keeping to orbit raising. The progression from early kW$_e$-class systems to the current SOA XR-5 4.5 kW$_e$-class system has been methodical and produced significant lessons learned (particularly with respect to facility effects) for application to ongoing and future development efforts. The next step in the progression is presently underway with the large-scale efforts to manufacture, test, and qualify both the 6 kW$_e$ BHT-6000 and 12.5 kW$_e$ AEPS systems for the PPE of NASA's Lunar Gateway. Major milestones for NEP Hall thruster CTE-4 developments well beyond the present efforts have been established and include:

- Optimization of thruster design (power level, materials, configuration) for MW$_e$-class modules,
- Demonstration of clustered thruster operation at power-levels and thruster cluster configurations relevant to MW$_e$-class NEP applications,
- Large-scale plume testing in a large test facility,
- Demonstration of PCU (either DDU or PPU depending on selection) technology using inputs emulating the expected output of a Brayton power conversion system as transmitted through a realistic PMAD emulator,
- Determination of an optimal propellant storage system (high-pressure supercritical or cryogenic) with a realistic demonstration of a relevant SS assembly,
- Development and validation of predictive models for thruster physics, plume impacts, and thermal management for thrusters operating in clustered modules, and
- Development of a detailed FMEA with risks and risk mitigation plans to guide Phase 3 development.

The major hurdles to consideration for selection for a high-power NEP mission are associated with the credibility of testing clustered high-power thrusters in ground-based facilities and projection of required endurance. Advances in cathode technology and the development of a realistic PCU (DDU or PPU depending on selection) are needed. Promising technology advancements have occurred over the last decade and implementing and validating these technology advancements is at the heart of the Hall technology advancement plan. Clear milestones, documented risks and risk mitigation strategies, and NAR oversight are all called out specifically in the advancement plan. As written, this plan will determine the efficacy of Xe-fed Hall systems and advance their maturity for high-power NEP flight applications.

6.5 MPD System Background, State-of-Art, and Technology Gaps

MPD thrusters are electromagnetic plasma accelerators that have been investigated experimentally and analytically since the 1960s. Typical MPD thrusters feature a coaxial configuration with a central cathode and a cylindrical anode, as shown in Figure 6.19.

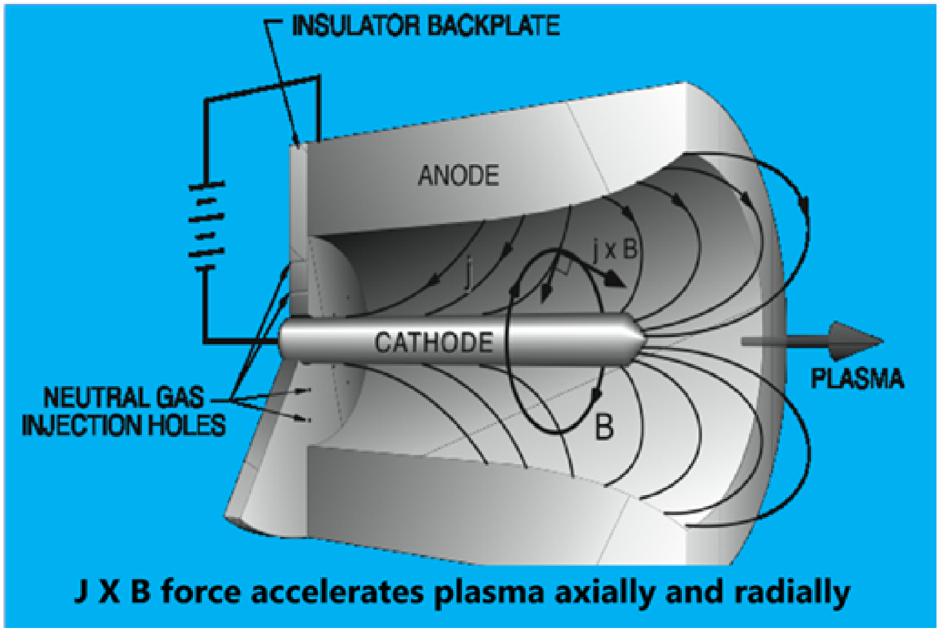


Figure 6.19: Simplified block diagram illustrating the operating characteristics of an MPD thruster.

In operation, a high-current arc is driven between the cathode and anode. The Lorentz body force ($\mathbf{j} \times \mathbf{B}$) generated by the interaction between the flowing current density ($\mathbf{j}$) and a self-induced magnetic field ($\mathbf{B}$) accelerates the propellant to the high velocities necessary for effective propulsion. At power levels below approximately 100 kW_e, an applied magnetic field is typically required to achieve thruster performance levels of interest for NEP applications (ref. [156]). At the higher MW_e-class power levels that this TMP contemplates, the self-magnetic field increases and the amount of power expended in propellant ionization as a fraction of the overall input power decreases, resulting in a thruster that yields efficient acceleration without the need for an applied magnetic field (ref. [220]).

For decades, MW_e-class MPD thruster research in the U.S. was performed in the “quasi-steady” mode in which a pulsed current is applied to the thruster for a period of time sufficient for the internal plasma properties and discharge current and voltage waveforms to roughly reach steady state (pulse lengths of hundreds of microseconds to a few milliseconds). Quasi-steady testing permitted high-power thruster operation without the need for steady-state high-power supplies or the commensurate pumping speeds required to maintain low vacuum levels at the required mass flow rates. From these data, high-power performance has been estimated and models of performance scaling have been derived. There was some steady-state thruster work on argon and hydrogen-fed devices in the 100-200 kW_e range under the

SEI program (ref. [157]). In addition, research and development up to the MW$_\mathrm{e}$-level has been performed at the Institute of Space Systems in Germany (refs. [221, 222, 223]).

Lithium-fed MPD thrusters were developed to a high level of maturity in the former Soviet Union in the late 1960s and early 1970s. Three different organizations built 500 kW$_\mathrm{e}$ thrusters, and all demonstrated thrust efficiencies of greater than 50% at I_{sp} values of $\sim$4000 s. One of these thrusters (the Energia model developed through a collaboration between the Scientific-Production Association "Energia" and the Scientific Research Institute of Thermal Processes) was tested for 500 hours at 500 kW$_\mathrm{e}$ and exhibited minimal anode erosion while operating at an I_{sp} and thruster efficiency of approximately 4,000 s and 60%, respectively. It is by far the longest test of a highpower NEP-class thruster of any type (ref. [154]). That test also suggested the potential of adding barium to the cathode propellant flow to reduce cathode operating temperatures and commensurate cathode erosion. The same group also fabricated a 1 MW$_\mathrm{e}$ engine and tested it for short durations. The scaling laws developed under this program (and through quasi-steady thruster testing performed at Princeton University from the late 1960s through the present) provide a solid foundation for performance predictions. Many of the approaches to achieving long thruster life were learned in these tests and have been incorporated as features of the current NEP maturation effort.

From 1994 to 1999 JPL funded steady-state MPD thruster research at the Moscow Aviation Institute (MAI) and Princeton University under the In-Space Transportation Program (ISTP) (ref. [155]) managed by the Marshall Space Flight Center (MSFC). The MAI effort focused on the development of applied-field lithium MPD thrusters at power levels ranging from 100 to 250 kW$_\mathrm{e}$. An MAI-developed high-power Li MPD thruster is shown in Figure 6.20.

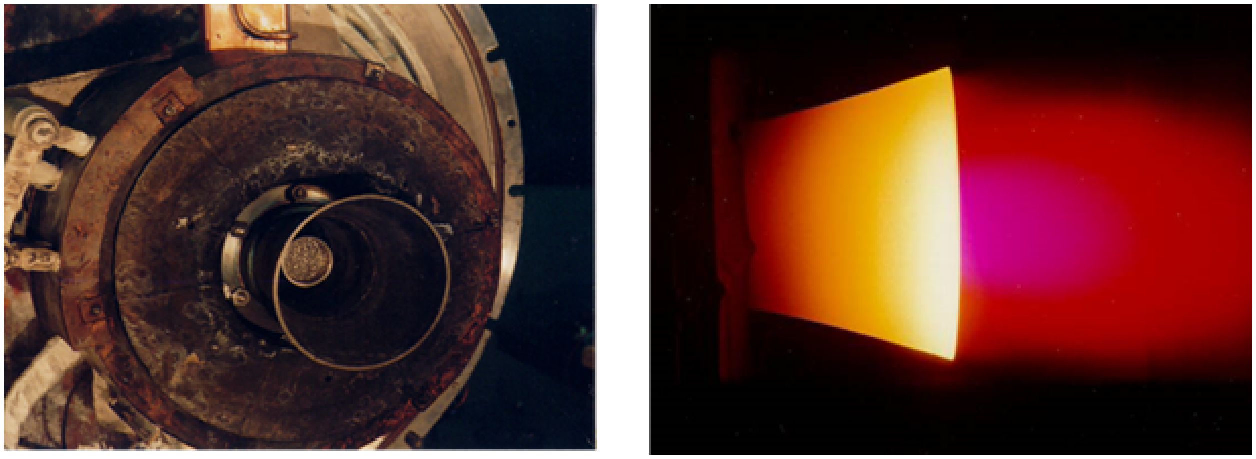


Figure 6.20: High-power Li MPD Thruster Developed at MAI. (installed hardware on left, 200 kW$_\mathrm{e}$ operation on right).

Like the previous 500 kW$_\mathrm{e}$ tests, the 250 kW$_\mathrm{e}$ work also demonstrated that the addition of barium to the propellant flow through the cathode can dramatically lower the cathode temperature in short duration tests (refs. [155, 158]). MAI also fabricated a 30 kW$_\mathrm{e}$ applied-field Li thruster that was delivered to Princeton University for testing. This unit was used in fundamental studies of applied-field MPD thruster performance scaling and electrode design. During this same timeframe JPL assembled a large condensable propellant vacuum test facility with the required cooling capability and available electric power to support testing up to 2 $\mathrm{MW_e}$. The collaborative work with MAI allowed JPL and Princeton researchers to learn the former's design methodology, develop refractory metal fabrication methods, and the develop the techniques needed to safely handle and test a thruster operating on Li propellant. These test procedures were implemented at Princeton and formed the core of JPL's lithium thruster test procedures and safety protocols.

In 2000, also under ISTP funding, JPL designed a 500 $\mathrm{kW_e}$ thruster and fabricated some of the key engine structural components, which are the basis for the 100 $\mathrm{kW_e}$ pathfinder engine proposed for the initial testing under this maturation program. In the previous program, JPL was employing the vacuum plasma spray facility at MSFC to fabricate large tungsten parts with mixed success. This plasma spray facility was subsequently spun off and is presently part of the core business of Plasma Processes, Inc. (PPI) in Huntsville, AL. Over the last few decades PPI has developed the capability to spray tungsten 2% rhenium solid rocket motor inserts, which are comparable in size to the anodes required for high-power MPD thrusters. This technology is the baseline for the fabrication of thruster anodes in the proposed MPD program.

MPD thruster technology was revisited in the JIMO/Project Prometheus era (2004-2005) in the Princeton-led Advanced Li-fed, Applied-field Lorentz Force Accelerator project (Project α^2). This short-lived program (the end of Phase I coinciding with the ending of JIMO/Project Prometheus) focused on a system power level of 250 $\mathrm{kW_e}$ and, despite its short duration, the project provided information in multiple areas relevant to high-power MPD research and development. These included, for example, the development of a Li vaporization system model, an assessment of Li-plume/ spacecraft interaction and contamination, investigation of Li electromagnetic pump (ref. [224]) and flowmeter (ref. [225]) technologies, and, perhaps most importantly, a cathode design developed for practical fabrication of flight-like units (ref. [158]). A 240 $\mathrm{kW_e}$ thruster was designed for operation at an I_{sp} of 6200 s and efficiency of $\geq$60%, applying electrode design lessons learned from the earlier MAI program. The designs from this program are the basis for the first NEP-project cathode to be fabricated for a 100 $\mathrm{kW_e}$ pathfinder Li-fed MPD thruster.

It is noted that, while MPD thruster technology was not recommended as a priority candidate for further development in the NESC report (ref. [28]), this report was written prior to the SNP TIMs and without conversations between the NESC panel and MPD SMEs. By contrast, the team that assembled the National Academies report on the readiness of nuclear propulsion technologies for human Mars missions did recommend the Li-fed MPD as a candidate propulsion technology (ref. [29]). For the CTE-4 TMP development, SNP held both pre- and post-TIM discussions with SMEs, including those that indicated MPD technology was a strong potential candidate for high-power NEP applications.

SME assessments offered at the EP TIM coupled with follow-on discussions suggest that the major areas of focused research and development for MPD advancement are:

- **Thruster Endurance**: The only successful high-power endurance test of appreciable duration (of any EPS candidate to date) was the previously discussed 500-hour/500 $\mathrm{kW_e}$ Russian Li-fed MPD test performed in the early 1990s. Test results were encouraging but indicated increasing cathode temperatures with time due to the depletion of low work function material. This phenomenon was projected to limit MPD electrode lifetime to durations well below the length of time needed to meet SNP goals. However, as a means of mitigating this effect, it was found that direct addition of barium (Ba) to the Li propellant flow may solve this issue. Investigating this mitigation method will be a major focus of early TRL 4 testing and a primary focus of the SNP MPD development and maturation plan. A major thruster endurance modeling effort is planned and both TRL 4- and TRL 5-sequence experiments will be designed to provide data for model validation.

- **PPU development**: The MPD thruster will likely employ a conventional PPU design as described by Rockwell (ref. [202]) with multiple input modules each composed of an AC-to-DC converter followed by a pulse-width modulated, closed loop constant current DC-to-DC converter. The DC-to-DC converter provides 1) final voltage adjustment to match the MPD I-V characteristics throughout the lifetime of the thruster and 2) fast current control required for non-damaging starts and stable steady-state operation. The AC-to-DC converter will be similar to the Hall converter but will be more massive and slightly less efficient that the Hall unit due to the lower operating voltage. At this point, the DC-to-DC converter is anticipated to be derived from technology developed in the ESEX program (ref. [142]). The ESEX PPU was designed for 30 $\mathrm{kW_e}$ operation, using three 10 $\mathrm{kW_e}$ modules to produce the necessary output. These modules should be scalable to 100+ $\mathrm{kW_e}$ with no need for new component development, however some components were custom designed (ref. [226]) and this technology base will have to be reconstituted. EPC Space has a GaN-based product line that includes 90A/200V components that might be adaptable for the MPD application. At 200V, the component already meets the NASA/industry derating factor of 2. SME inputs indicate that higher current parts may be possible but their development would require research on packaging due to anticipated thermal issues. As with the WBG technology for Hall thrusters noted above, the most recent developments in GaN WBG components will be reviewed at the opening workshop with an expected result of a recommendation to SNP on whether or not to pursue WBG technology. Early development efforts will include a focused study to optimize the PMAD/EPS (CTE- 3/CTE-4) interface to determine the optimal interface topology (e.g., transformer, AC-to-DC converter/PPU design and input module sizing). The ESEX PPU had an efficiency of 95% and this was assumed in deriving the efficiencies shown as KPPs in Table 6.9.

- **Heat rejection**: Thermal management in both the thruster and the PPU will be major issues to address for an MPD. The thruster glows when operating and radiatively rejects a significant portion of heat to space, but there is still the potential for thermal soak-back into the rest of the system. In addition, to maintain the Li propellant in a liquid state, it must be kept at elevated temperatures from the propellant tank to the thruster where it is vaporized and injected into the discharge. Finally, even a very efficient PPU will generate a significant amount of heat that must be managed and eventually rejected to space. While there may not be as many thrusters in a cluster compared to a Hall-based system, the design may still include multiple thrusters and PPUs located in close proximity, reducing the solid angle over which heat can be rejected without affecting neighboring units. All of these issues will require detailed thermal design and testing to quantify thermal performance and induced thermal environments for CTE-4.

- **Transient behavior**: High current transients can rapidly damage hardware. While apparently not a major issue in the 500 $\mathrm{kW_e}$ Russian tests, spot-mode operation on the anode at startup is a major concern based on SME inputs. The dynamic nature of MPD startup will be a major focus of early testing efforts, especially as part of the initial 100 $\mathrm{kW_e}$ testing planned using COTS PPU hardware. Findings will be closely monitored and fed back to the PPU development team to assure the PPU interface has the dynamic capabilities to handle electrical transients.
- **Plume impacts**: To date, there has been very little experimental or M&S research on the impact of high-power Li MPD thruster plumes. Both facility effects and the back fluxes of propellant and any sputtered materials must be considered. For this, large scale plume testing in a large facility (with requirements to be defined at a Q1/Y1 workshop) is planned. A major plume modeling effort is also planned and both TRL 4- and TRL 5-sequence experiments will be designed to provide data for model validation.

Table 6.9: KPP Guidance for MPD EPS Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Power per Thruster (MW_e)	0.5	1.0	1 MW_e "building blocks" are key to overall technology maturation strategy – decision on power per thruster midway through TRL 4 testing.
CTE-4 MPD α (per string in kg/kW_e)	5	3	Threshold and target values derived from mission analysis and SME technical inputs (Refs. [142, 156])
Thruster Performance	η and I_{sp} shown in Figure 2.1		Performance values based on experimental data obtained from SNP SMEs. Performance projection from SOA sufficient for mission closure – no research and development required for performance improvement. (Curve represents nominal expected performance from available data. Mission modeling assumes ±5% absolute uncertainty to estimate mission closure mass impact.)
PPU Efficiency (η in %)	93	95	Threshold and target η values derived from mission analysis and SME technical inputs (Refs. [142, 156])
Total thruster operating time (hours)	27,000	32,000	Threshold provides margin for single (2.5 year) human mission to Mars, including allocation for spiral up from aggregation orbit; target enables multi-trip reuse. Includes spiral up. Operating time assumes an approximate 10,000 hr spiral time from low-Earth orbit (LEO) to near-rectilinear halo orbit (NRHO). Thruster lifetime requirements would be significantly reduced with direct injection to (or assembly in) NRHO.
Radiation limits	n (>100 keV): 10^{12} n/cm^2 Gamma: 100 krad		Projected neutron (n) and gamma dose limits for power electronics.

6.6 MPD Technology Requirements and Advantages

Advancements to date and projections for future high-power, modular systems make MPD technology a primary candidate for NEP applications. SNP mission modeling in conjunction with SME inputs has provided the preliminary KPPs shown in Table 6.9 as guiding requirements.

Multiple major features make a Li-fed MPD propulsion system a desirable NEP candidate. These include:

1. **Ability to ground test at full scale**: Thruster uses a condensable propellant (Li) that can be pumped at high speeds using simple refrigerated cold plates without need for the deep cryogenic pumping capabilities required for devices that consume noble gases. This feature makes testing a complete propulsion system at full power in available and/or readily modifiable vacuum test facilities possible. It is also relatively straightforward and potentially a relatively low-cost endeavor to engineer and assemble a new vacuum facility at a site where a nuclear reactor can be operated, supporting potential end-to-end NEP system testing. testing.
2. **High power density**: The ability to process high power levels using a small number of relatively small/lightweight units provides options for redundancy and flexibility in operating at derated power levels that are not possible with other thruster options. Engineering concept sketches of a $\mathrm{MW_e}$-class single thruster and a two-thruster pod (with each thruster capable of 1 $\mathrm{MW_e}$ power throughput for full redundancy) are shown in Figure 6.21. The mass of a single 1 $\mathrm{MW_e}$ thruster is estimated to be 200 kg.
3. **Propulsive performance range**: A Li-fed MPD with an I_{sp} range of 4,000-7,000 s at thruster efficiencies (η) of $\sim$60% is expected based on experimental measurements and modeling efforts performed in Russia and the U.S.
4. **PPU technology status**: The technology developed for the 30 $\mathrm{kW_e}$-class PPU that was flight-qualified and flown in the 1999 Air Force ESEX (ref. [142]) is directly applicable to high-power MPD systems. The ESEX architecture can be used as the fundamental building block in a large-scale modular PPU system, with no major new component or technology development required.
5. **Propellant availability**: In 2020, world production of Li was 82,000 MT (ref. [227]), which was down from its peak of 85,000 MT in 2018 but still more than a 3-fold increase from the 28,000 MT in 2010. The price of Li metal was reduced in the 2020 timeframe as the production of the metal outpaced the supply needs of the electric vehicle (battery) industry (ref. [228]). The total amount of Li needed for an entire NEP human Mars campaign, including developmental testing, is a small fraction of the world supply in a single year and would be readily available for procurement.
6. **Propellant storage**: Lithium would be stored as a solid during launch and could provide structural rigidity to reduce launch vibration issues. Standard stainless steel (such as SAE 304) is sufficient for the propellant tanks with the Li melted and residing in the tanks as a low-pressure liquid during flight. A likely Li propellant management

system could be very similar to those currently in use for controlling the flow of liquid Li in fusion research experiments (ref. [229]).

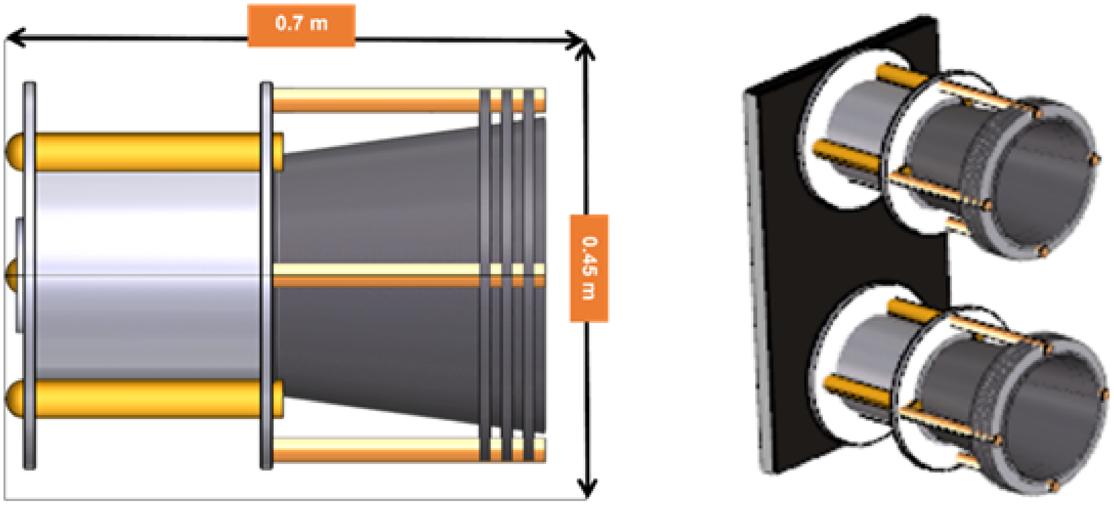


Figure 6.21: Artist conceptions (left) MW_e-class MPD thruster and (right) two-thruster fully redundant MW_e class thruster pod (each thruster capable of MW_e-class operation).

Table 6.10 shows major aspects/gaps in CTE-4 requiring focused MPD technology research and development and a brief description of the advancements needed to move MWe-class MPD thruster technology from its present readiness level to TRL 5. More detail on the development effort and the risks and risk mitigation plans associated with these efforts are provided in the following sections.

Table 6.10: Major MPD Technology Aspects and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
1	Cathode	Demonstrate cathode temperatures low enough to permit long endurance operation using multi-channel hollow cathodes, stepping up the power incrementally to 100 kW_e, then 500 kW_e, and finally 1 MW_e. The 500 kW_e testing will be performed at the BB level of thruster hardware fidelity with advancement to 1 MW_e testing using BrB-fidelity hardware. A predictive cathode model will be developed and validated with available test data to project cathode life to >15,000 hours.

Table 6.10: Major MPD Technology Aspects and Advancement Requirements.

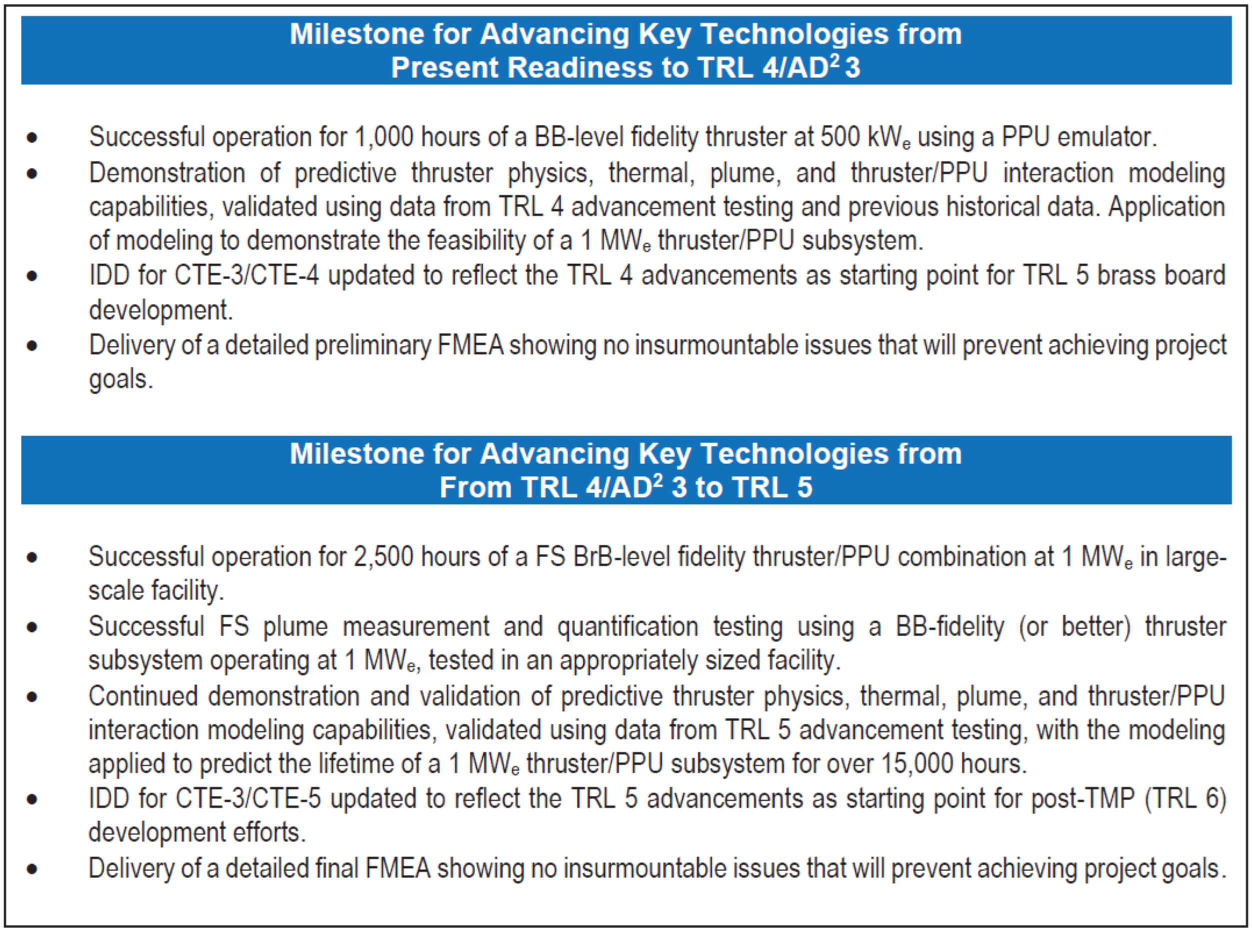
	Technology Description	**Advancement Descriptions**
2	Anode	Demonstrate an anode design through 500 kW$_e$ and 1 MW$_e$ testing showing minimal to no erosion. Develop predictive anode models and validate with available data to project anode life to >15,000 hours. The 500 kW$_e$ testing will be performed at the BB level of thruster hardware fidelity with advancement to the 1 MW$_e$ testing using BrB hardware.
3	Thruster Performance	Demonstrate acceptable sustained performance (I_{sp}~4,000 to 6,000 s with thrust efficiencies greater than 60% over this I_{sp} range) during long duration testing.
4	Power Processing Unit	Conduct a progressive fabrication/modeling/test program that results in the demonstration of two 500 kW$_e$ BrB fidelity PPUs ganged together to support a 1 MW$_e$ long-duration endurance test. This will be preceded by a progression from laboratory emulators in 100 kW$_e$ testing to BB hardware fidelity PPU testing at 500 kW$_e$. A detailed model of the PPU/thruster interface will be developed to evaluate test findings and guide future advancement.
5	Propellant Management	Drawing from the ongoing Li fluid management systems currently used in fusion research, the project will develop a BrB propellant management system prior to the initiation of 500 kW$_e$ thruster testing. This system will at a minimum be demonstrated during plume quantification testing in a large-scale facility with a thruster operating at 1 MW$_e$.
6	Propellant Storage	A flight-like low-pressure stainless-steel tank (SAE 304) of a size determined as part of the effort will be fabricated to demonstrate thermal management, propellant melting, and to serve as a source for testing the propellant management system.
7	Plume Impacts	Detailed models of thruster-to-spacecraft electrical interactions and potential plume impingement and contamination impacts will be developed to inform future spacecraft system designs. The models will be upgraded in each phase of the testing to the extent possible using available experimental data, with final validation in a FS 1 MW$_e$ thruster test to be performed in a large facility.

Table 6.10: Major MPD Technology Aspects and Advancement Requirements.

	Technology Description	**Advancement Descriptions**
8	Overall Thruster Subsystem	The thruster subsystem carries the TRL/AD^2 of the least mature component of the subsystem. Advancement will progress through a series of tests from a lab model fidelity test at 100 kW$_e$ to demonstrate facility capabilities and verify component design, to BB-fidelity testing at 500 kW$_e$, and finally to BrB fidelity testing at 1 MW$_e$. Detailed models for design (for thruster performance, thermal management, and dynamic response/vibration considerations) and to quantify plume impacts and provide insights into mitigation strategies, will be developed in parallel to the experimental effort.

6.7 MPD Technology Advancement Plans

The SNP project has developed a methodical approach to the advancement of high-power MPD technology from its present readiness level to the TRL 5. SNP-supported SMEs with technology infusion experience have reviewed MPD technology as it applies to a MW$_e$-class NEP system and established the advancement goals outlined in Figure 6.22.



Milestone for Advancing Key Technologies from Present Readiness to TRL 4/AD^2 3

- Successful operation for 1,000 hours of a BB-level fidelity thruster at 500 kW_e using a PPU emulator.
- Demonstration of predictive thruster physics, thermal, plume, and thruster/PPU interaction modeling capabilities, validated using data from TRL 4 advancement testing and previous historical data. Application of modeling to demonstrate the feasibility of a 1 MW_e thruster/PPU subsystem.
- IDD for CTE-3/CTE-4 updated to reflect the TRL 4 advancements as starting point for TRL 5 brass board development.
- Delivery of a detailed preliminary FMEA showing no insurmountable issues that will prevent achieving project goals.

Milestone for Advancing Key Technologies from From TRL 4/AD^2 3 to TRL 5

- Successful operation for 2,500 hours of a FS BrB-level fidelity thruster/PPU combination at 1 MW_e in large-scale facility.
- Successful FS plume measurement and quantification testing using a BB-fidelity (or better) thruster subsystem operating at 1 MW_e, tested in an appropriately sized facility.
- Continued demonstration and validation of predictive thruster physics, thermal, plume, and thruster/PPU interaction modeling capabilities, validated using data from TRL 5 advancement testing, with the modeling applied to predict the lifetime of a 1 MW_e thruster/PPU subsystem for over 15,000 hours.
- IDD for CTE-3/CTE-5 updated to reflect the TRL 5 advancements as starting point for post-TMP (TRL 6) development efforts.
- Delivery of a detailed final FMEA showing no insurmountable issues that will prevent achieving project goals.

Figure 6.22: Key Milestones in the EPS MPD Technology Advancement Strategy.

Table 6.11 and Table 6.12 provide a more detailed description of the major milestones with respect to advancement of the MPD thruster/PPU subsystem to TRL 4/AD^2 3 and then to TRL 5, respectively, and their relative timing (under the assumption that authority to proceed is given in Q1 of a fiscal year). Table 6.13 and Table 6.14 provide the anticipated milestones and timelines for propellant system maturation and facility development, respectively. The detailed schedules for these advancements are shown in Figure 6.23.

Table 6.11: MPD Thruster/PPU Maturation Path - present status to TRL 4 and AD^2 3 at 500 kW$_e$.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
SME Workshops on Thruster, PPU, M&S, FMEA	CTE4-5.1	Q1/Y1	SME review of status of currently-available hardware, M&S, and FMEA requirements for all aspects of MPD system – design, fabrication, plume, thermal, structural, electrical interfaces, and performance. Workshops establish baseline advancement directions. Preliminary risks and hazards lists generated.
500 kW$_e$ Thruster Preliminary Design Complete	CTE4-5.2	Q3/Y1	SME-developed thruster design (adapted from prior 500 kW$_e$ unit) developed and submitted to SNP for review.
M&S/FMEA Plans in Place	CTE4-5.3	Q2/Y1	Plans for step-by-step analysis of potential failure modes, impacts and mitigations in place. First draft to concentrate on potential failure scenarios in the planned MPD system test program and rapid mitigation plans. Comprehensive M&S plans distilled from workshop, and other SME, inputs.
Preliminary PPU Design Complete	CTE4-5.4	Q2/Y1	SME-generated 500 kW$_e$ (gangable) PPU design developed for SNP review. Authority to proceed to BB development stage.
Lab PPU Delivered	CTE4-5.5	Q3/Y1	COTS PPU emulator delivered and available for BB testing.
100 kW$_e$ TRR	CTE4-5.6	Q4/Y1	SNP test readiness review complete. Authority to start 100-hour shakedown test.
Preliminary M&S/FMEA Reports Complete	CTE4-5.7	Q4/Y1	First (pre-test) draft of FMEA and individual M&S products (structural, thermal, plume, etc.) complete, reviewed by SME's and approved by SNP for further development.
Initial IDD Draft Complete	CTE4-5.8	Q4/Y1	SME developed interface description document developed, reviewed, and delivered to SNP SE&I lead.
BB Thruster & PPU Designs Complete	CTE4-5.9	Q4/Y1	BB-class thruster and 500 kW$_e$ PPU designs complete with SNP review and authority to proceed to procurement and fabrication (note: decision on 500 kW$_e$ vs 1 MW$_e$ thruster).
Interim SME BB Plan Review (w/ Included Plume Event)	CTE4-5.10	Q1/Y2	SME review to assure direction of thruster/PPU hardware under development for BB testing at 500 kW$_e$ and recommend test requirements (e.g., structural and thermal).

Table 6.11: MPD Thruster/PPU Maturation Path - present status to TRL 4 and AD^2 3 at 500 kW_e.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
SNP Midterm Progress	CTE4-5.11	Q2/Y2	SNP review of all aspects of the MPD development - FMEA and M&S progress updated using inputs from both the ongoing 100 kW_e; and the 500 kW_e thruster/PPU development progress.
100 kW_e Test Complete with SME Review	CTE4-5.12	Q3/Y2	SME review of 100 kW_e shakedown test results – data packages with lessons learned provided to team members for guidance in M&S and FMEA development as appropriate.
BB PPU & Thruster Delivered/Installed	CTE4-5.13	Q3/Y2	All BB hardware required for TRL 4 BB testing delivered and installed, SME inspection prior to TRR completed. It is noted that environmental testing (e.g., vibration and thermal) will precede this step if recommended by SNP SMEs.
500 kW_e BB TRR	CTE4-5.14	Q3/Y2	SNP review of 500 kW_e test hardware and test plan readiness – authority to proceed with 1,000-hour testing.
Interim SNP 500 kW_e Test Progress Review	CTE4-5.15	Q4/Y2	SNP review of ongoing BB test at the 100-hour point – review to include thruster/PPU operating characteristics/performance.
Interim SME M&S Review	CTE4-5.16	Q1/Y3	Review of all M&S efforts (plume, thermal, structural, etc.) after updates using data from ongoing 500 kW_e BB test.
500 kW_e 1,000-hour Test Complete	CTE4-5.17	Q3/Y3	1,000-hour BB thruster/PPU test completed – SME review of results with recommendations for BrB phase. Project report to NA panel for pre-NAR assessment.
TRL 4 M&S/FMEA Reports Delivered & TRL 4 NAR	CTE4-5.18	Q3/Y3	NAR for advancement of CTE-4 MPD technology to TRL 4.
IDD and Risk & Hazards Lists Complete	CTE4-5.19	Q3/Y3	TRL 4 IDD revised as necessary for BrB emulator development – delivered to SNP SE&I lead. Revisions to risk and hazards lists complete and delivered to SNP.

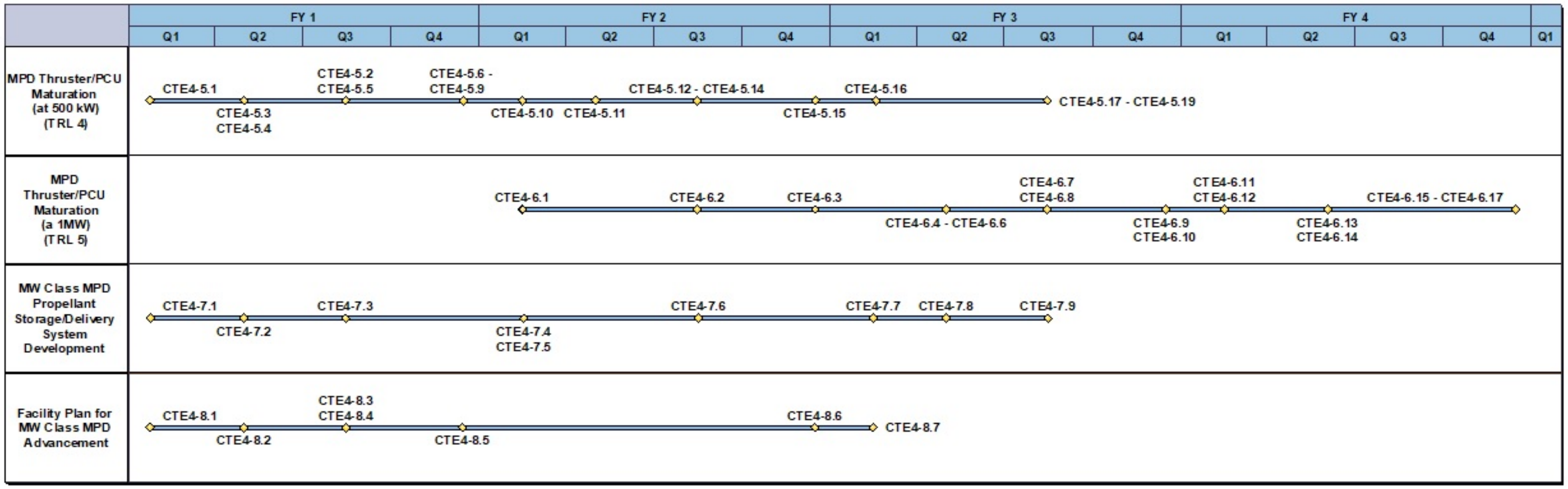


Figure 6.23: CTE 4 MPD Thruster Advancement Schedule.

Table 6.12: MPD Thruster/PPU Maturation Path - TRL 4 and AD^2 3 to TRL 5 at 1 MW$_e$. (* If decision was made in step 15 of Table 6.11 to keep thrusters at 500 kW$_e$, all 1 MW$_e$ thruster tasks will require two of 500 kW$_e$ thrusters.)

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
BrB Design Review (500 kW$_e$ PPU & 1 MW$_e$ Thruster)	CTE4-6.1	Q1/Y2	SME review of hardware development efforts for BrB-class thruster and PPU. Provides assurance that lessons-learned from BB hardware fabrication & testing are incorporated. Authority to proceed with long-lead delivery component acquisition. Hazard and risk lists reviewed and updated as necessary.
BrB 500 kW$_e$ PPU & 1 MW$_e$ Thruster Designs Complete	CTE4-6.2	Q3/Y2	BrB thruster and PPU designs complete with SNP review – authority to proceed to full fabrication phase.
Interim PPU Development Review	CTE4-6.3	Q4/Y2	SME review of PPU hardware development progress with report to SNP (recommendations for modifications, if necessary).
BrB Thruster & PPU Delivery & Installation	CTE4-6.4	Q2/Y3	BrB thrusters and PPU(s) delivered and installed in preparation for TRL 5 testing (endurance and plume testing). It is noted that environmental testing (e.g., vibration, shock, and thermal) will precede this step if recommended by SNP SMEs.
BrB Hardware Inspection & Plan Reviews (Plume and Endurance)	CTE4-6.5	Q2/Y3	SME review of installed hardware and BrB test plans with readiness assessment report to SNP.
Large-Scale Plume Test Plan Review & Endurance Shakedown TRR	CTE4-6.6	Q2/Y3	Concurrent SNP review to assure 1) large-scale plume facility, diagnostics, and test plan will provide quality M&S inputs and 2) test readiness (with authority to proceed) for endurance hardware shakedown 500-hour test at 500 kW$_e$.
Interim review of 500 kW$_e$ Shakedown Test and LS Plume Test TRR	CTE4-6.7	Q3/Y3	Concurrent SNP review to 1) assess 500 kW$_e$ shakedown progress with authority to continue and 2) readiness for large-scale plume testing with authority to proceed.
Midterm M&S/FMEA Review	CTE4-6.8	Q3/Y3	SME review of 1) current FMEA (updated based on BB and 250-hour BrB tests at 500 KW$_e$) and 2) all M&S results and readiness for modeling (with requirements for validation) of MW$_e$-class system.
1 MW$_e$ Endurance TRR	CTE4-6.9	Q4/Y3	500-hour 500 kW$_e$ shakedown test report delivered, SNP review to assure test readiness for 2,500 hour endurance test (authority to proceed).

Table 6.12: MPD Thruster/PPU Maturation Path - TRL 4 and AD^2 3 to TRL 5 at 1 MW_e. (* If decision was made in step 15 of Table 6.11 to keep thrusters at 500 kW_e, all 1 MW_e thruster tasks will require two of 500 kW_e thrusters.)

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Interim Large-Scale Plume Test Review	CTE4-6.10	Q4/Y3	SME review of ongoing large-scale data, data available for M&S updates – report to SNP with recommendation to continue testing or for modifications, if required.
Interim M&S/FMEA Review	CTE4-6.11	Q1/Y4	SME review of both FMEA and thruster (plume and thermal) modeling progress (after early endurance and plume test data incorporation).
Interim BrB Test Progress Review	CTE4-6.12	Q1/Y4	SNP review of BrB MPD endurance test results at the 250-hour mark – authority to continue to 2,500-hour goal.
Large-Scale Plume Test Complete/Review	CTE4-6.13	Q2/Y4	SME review of large-scale plume test results – report to SNP on adequacy for model validation and recommendation for test extension, if warranted.
Final TRL 5 M&S/FMEA Report Drafts Submitted	CTE4-6.14	Q2/Y4	FMEA and M&S updated with incorporation of data from plume and endurance testing – report to SNP.
BrB Test Complete/Review	CTE4-6.15	Q4/Y4	2500-hr test complete – thruster system disassembled, inspected, and documented. Lessons-learned formulated to support next test phase (prototype development). Decision on potential continuation of endurance test beyond 2,500 hr.
TRL 5 NAR	CTE4-6.16	Q4/Y4	NAR for advancement of CTE-4 MPD technology to TRL 5.
Final IDD and Risk & Hazards Lists Complete	CTE4-6.17	Q4/Y4	Final IDD revised as necessary for BrB emulator development – delivered to SNP SE&I lead. Revisions to risk and hazards lists complete and delivered to SNP.

Table 6.13: MW_e-Class Propellant Storage/Delivery System Development (to TRL 5).

Major Technology Milestones	**#**	**Timeframe (End Date)**	**Significance**
Propellant System Design Workshop	CTE4-7.1	Q1/Y1	SME-led workshop report to evaluate all available information and recommend storage strategy (e.g., tank design, ganging, thermal control) to SNP. Evaluation of propellant delivery system component status (with in-depth review of European fusion energy program hardware International Thermonuclear Experimental Reactor) to recommend focused research and development, if required.
BB Propellant System Design Complete	CTE4-7.2	Q2/Y1	SME review of design and evaluation of available components. Report to SNP, acquisition of long-lead items initiated.
BB (500 kW_e) System IOC	CTE4-7.3	Q3/Y1	BB system delivered/installed/inspected with report to SNP. SNP review of BB propellant system readiness for testing. Approval to proceed.
BB Propellant System Test Complete/Review	CTE4-7.4	Q1/Y2	100-hour test of BB propellant system completed, SME review of performance with report to SNP on lessons learned and recommendations for modifications for BrB development, if warranted.
BrB Propellant System Design Workshop and Development Kickoff	CTE4-7.5	Q1/Y2	SME workshop to evaluate lessons learned from BB advancement and develop optimal design for BrB system (including minimum tank sizing). Report with recommendations to SNP.
BrB Propellant System Design Complete/Review	CTE4-7.6	Q3/Y2	SNP review of BrB design – authority to proceed.
BrB Propellant System Hardware Delivered & Installed	CTE4-7.7	Q1/Y3	BrB propellant system assembled and installed for MW_e testing (if required) – SME inspection with recommendation to proceed (with modifications if warranted).
Integrated BrB System TRR	CTE4-7.8	Q2/Y3	SNP review of FS propellant system – authority to proceed.
Integrated BrB Test Complete/Review	CTE4-7.9	Q3/Y3	BrB propellant system competed – SME review with report to SNP (system validated or recommendation for further testing, if warranted).

Table 6.14: Facility Plan for MW_e-Class MPD Advancement from SOA to TRL 5.

Major Technology Milestones	**#**	**Timeframe (End Date)**	**Significance**
Facility Workshop	CTE4-8.1	Q1/Y1	Workshop to develop preliminary facility requirements for TRL 4 and TRL 5 testing. Identification of potentially available facilities initiated with instructions to develop detailed upgrade requirements for leading candidates.
Requirements for TRL 4 Testing Facilities Complete	CTE4-8.2	Q2/Y1	SME review of facility requirements for TRL 4 testing – facility selection by SNP.
TRL 4 Facility IOC/Review	CTE4-8.3	Q3/Y1	Facility operational for BB testing for a minimum of 500 kW_e – SME review of all capabilities needed to conduct advancement testing for TRL 4 with report to SNP.
TRL 5 Requirements Specification Complete with Facility Selection	CTE4-8.4	Q3/Y1	SNP review of comprehensive (plume and endurance) facility requirements – recommendation for facility (or facilities) selection – Note: one large facility or a combination of two facilities – e.g., continuation of endurance testing in HPCMTF and a larger facility for the plume test or combined testing in a large facility). SNP selection of a path forward.
TRL 5 Facilities Plan Complete/Review	CTE4-8.5	Q4/Y1	SME-developed facility upgrades for TRL 5 testing fully defined, SNP review and approval to proceed.
TRL 5 Facilities Upgrades Complete/Review	CTE4-8.6	Q4/Y2	SME review of TRL 5 testing-required upgrades complete with report to SNP (acceptance or recommendations for modifications).
TRL 5 Facilities IOC	CTE4-8.7	Q1/Y3	SNP review of upgraded test facilities complete – operational readiness confirmed.

Major schedule objectives include, for example:

- Initial testing in JPL's High-Power Condensable Metal Test Facility (HPCMTF), shown in Figure 6.24, using a 100 kW_e MPD thruster that incorporates a multi-channel hollow cathode with a continuous Ba resupply, leveraging components and designs completed under earlier programs (see, for example, ref. [156]). This testing will 1) demonstrate the capability of the facility to test high-power condensable metal thrusters upon reopening after the COVID-19 pandemic, 2) demonstrate the efficacy of the cathode technology, 3) provide 100 kW_e thermal and plume data for the advancement of models initiated and originally developed under the α^2 project, and 4) better define the thruster/PPU interface using high-quality PPU emulators.

- Testing with a BB-fidelity thruster/PPU system at power levels up to 500 kW_e. This extended testing (1000 hours) at the 500 kW_e power level will provide data to support system, thermal, plume, and thruster/PPU interface modeling. It is the intent of the project to perform these tests using a MW_e-class thruster, derated for this test sequence due to PPU limitations, which are addressed in this phase through separate tasks. Analyses performed to assure that this design is compatible with projected thermal vacuum, dynamic shock, and vibrational requirements. The extent of environmental testing (e.g., vibration and thermal) will determined by SME review of modeling data and "as built" hardware evaluations. The BB PPU design will be a modular design capable of being ganged for higher power operation. Finally, it is noted that, without a specific spacecraft design, PPU technology will be designed to reject the required heat to a notional interface without any dependence on ancillary spacecraft systems.

- Testing with a BrB-fidelity thruster/PPU system at the full 1 MW_e power level to demonstrate the system for a minimum of 2,500 hour and provide test data to support model advancement to a level capable of projecting the thruster lifetime required for the subject mission.

- Large-scale plume testing with hardware of at least BB-fidelity in a large facility capable of yielding high-quality data on plasma plume characteristics to fully validate plume models and for use in thruster plume-spacecraft interaction and mitigation assessments.

Figure 6.24: Jet Propulsion Laboratory High Power Condensable Metal Test Facility.

Major advancements in the field of Li fluid management have been achieved in the support of ongoing fusion research (ref. [229]). Lithium would be stored as a solid at launch and melted upon reaching orbit, yielding a low-pressure liquid propellant that can be contained using simple, low pressure stainless-steel tanks. The preliminary approach for propellant storage and delivery system development is shown in Table 6.13. The propellant system in the existing HPCMTF will be upgraded (as required) to address any development issues prior to BB and BrB propellant management system fabrication. Note that it is possible for the program to proceed directly to BrB design and fabrication and a recommendation on this path is an expected output of the SME Q1/Y1 workshop – the table currently shows both BB and BrB developments.

Possessing the necessary facilities capable of supporting high-power EP testing is always a major concern for such a development program. Of all propellants under consideration, Li is the least challenging in this regard due to its relatively high condensation temperature (boiling point of 1603 K). This means that a simple refrigerated cold-plate system can be used to condense (‘pump’) Li vapor, maintaining space-like vacuum conditions without the need for cryogenic-temperature coolers. A unique facility is already in place at JPL and capable of supporting this testing for SNP. Use of this facility is planned for the 100 $\mathrm{kW_e}$ and 500 $\mathrm{kW_e}$ test campaigns. This facility is also sufficient for FS endurance testing at 1 $\mathrm{MW_e}$. It will not, however, be sufficient for large-scale plume testing required to complete the plume assessment needed to achieve TRL 5. A methodical approach to defining the proper facility to support this testing is planned for early in the project starting with the initial facility workshop. The plan is to identify an available, large-scale facility and initiate required upgrades by the end of the first year of the program. The facilities advancement milestones and their significance are show in Table 6.14.

6.8 CTE-4 MPD Technology Advancement Risks

The SNP project has performed a preliminary development risk assessment of the MPD system with the support of non-advocate SMEs. The assessment exercise is the starting point for the formal FMEA, the results of which will be documented as part of the overall MPD technology development efforts (see Table 6.12 and Table 6.13). Table 6.15 shows the ‘Top 5’ technical risks identified at this point by SNP SMEs. As shown in the table, all risks will be fully described with risk assessments using NASA’s standard risk scale for consequence and likelihood (ref. [217]). Figure 6.25 captures these in the standard NASA risk matrix format.

Table 6.15: ‘Top 5’ EPS MPD Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
MPD-1	Cathode Erosion	Planned design incorporating both continuous Ba-feed and multi-channel hollow cathode technologies insufficient for required (over 15,000 hour) life projection.	T	3	3	9	Re-initiation of cathode physics and design M&S started under the α^2 program to develop advanced longer life cathode alternatives with at least one available for implementation by Q2/Y3. Early assessments of efficacy in 100 kW_e and 500 kW_e testing with SME evaluations. Design and acquisition of multiple components including both primary design spares and additional hardware for implementation of alternate design options as initial test results are evaluated. Fully funded schedule reserve for test iterations with technology infusion (if required) in each test sequence.

Table 6.15: ‘Top 5’ EPS MPD Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
MPD-2	Unacceptable Anode Operating Mode(s) or Erosion	Unanticipated anode behavior at power levels above 500 kW_e projected to limit lifetime below what is required or limit performance to unacceptable levels.	T	2	3	6	Initiation of anode physics and design M&S to develop alternative operating conditions and/or nozzle designs that avoid both the spot-mode high anode voltage fall regime and the sputtering operational regime, with at least one anode ready for implementation by Q1/Y3. Early assessments of efficacy in 100 kW_e and 500 kW_e testing with NAR evaluations. Design and acquisition of multiple components including both primary design spares and additional hardware for implementation of alternate design options as initial test results are evaluated. Fully funded schedule reserve for test iterations with technology infusion (if required) in each test sequence.

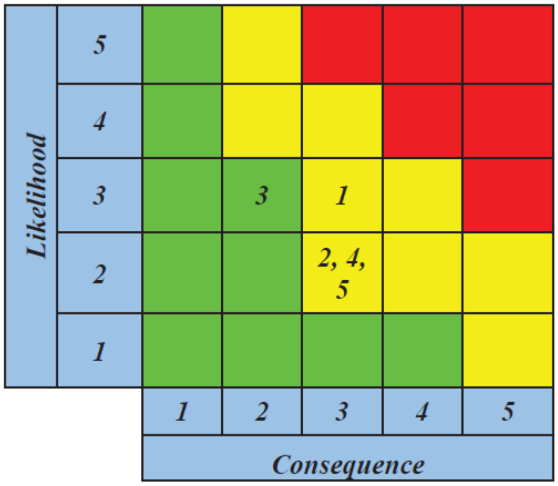
Table 6.15: ‘Top 5’ EPS MPD Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
MPD-3	PPU Module Integration	Engineering issues associated with the ganging of ESEX technology-based 30 kW_e-class modules into 500 kW_e unit.	T	3	2	6	Early assessment of required PPU/thruster interface via 100 kW_e testing with PPU emulators at outset of testing. Early 500 kW_e design initiation with >1 year design and fabrication cycle that will include extensive BB testing using plasma thruster simulators (preferably actual thrusters). Fully funded schedule reserve for design improvements (if required) in both 500 kW_e and 1 MW_e testing. Provision to implement and demonstrate final design iterations in either FS plume or endurance testing.

Table 6.15: ‘Top 5’ EPS MPD Thruster system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
MPD-4	Electrical Transient Response	Inability of PPU to handle starting transient behavior	T	2	3	6	Early transient assessments at 100 kW_e using flexible PPU emulators to optimize starting procedure. Stepwise testing to 500 kW_e with BB-fidelity hardware to identify transient starting issues and develop an optimal starting strategy (e.g., current ramp-up). Fully funded schedule reserve for design improvements (if required) in both 500 kW_e and 1 MW_e testing. Provision to implement and demonstrate final design iterations in either FS plume or endurance testing.
MPD-5	Thruster Performance Deficiency	Thruster performance (thrust efficiency at selected I_{sp}) insufficient to meet performance requirements projected for nominal mission application.	T	2	3	6	Early assessment of performance in stepwise fashion at power levels above self-field mode transition ($\geq$500 kW_e). Evaluation of performance repeatability at 500 kW_e in testing to advance to TRL 4. Fully funded schedule reserve for design improvements (if required) in both 500 kW_e and 1 MW_e testing.

- **Risk MPD-1**: The primary risk for the Li-fed MPD system as identified through SNP SME review is cathode degradation that can limit MPD endurance to less than



Likelihood 5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩 3	🟨 1	🟨	🟥
2	🟩	🟩	🟨 2, 4, 5	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5
	Consequence				

Figure 6.25: EPS MPD Thruster "Top 5" Risk Ranking Likelihood and Consequence Span.

the required lifetime (with margin). The key to long cathode life is maintenance of the cathode temperature to T≤2273 K. Past use of refractory materials with low work function material additives have not been effective for long-duration testing as these additives are rapidly depleted. This is the case even for the multichannel cathode design tested by MAI and Princeton. The addition of a low work function element (e.g., Ba) directly to the propellant has been shown to be effective in maintaining low cathode temperatures and this cathode technology will be employed in all planned thruster testing. Operation for over 100 hours at 500 kW_e will support an initial assessment of cathode degradation and yield data for model validation and support potential additional modification decisions (e.g., Ba-loading) that may be required prior to 500 kW_e testing. This will be an iterative process until a solution is attained that reduces the risk to an acceptable residual level. As noted, the planned test periods are all at least twice as long as is required to operate for the given number of hours, allowing extra time to implement any needed design iterations. If, however, acceptable cathode temperatures are not maintained through the planned 500 kW_e endurance test, the planned TRL 4/AD^2 3 exit NAR would likely be an off-ramp that eliminates the MPD from further consideration.

- **Risk MPD-2**: MW_e-class MPD thrusters are inherently high current devices (10-15 kA or greater) and the electrons impart significant energy (10-30% of the total) to the anode/nozzle as they conduct current. The anode will rapidly degrade if this energy is deposited in a localized spot mode on the anode surface. While damage of this type was not observed in the Russian 500 kW_e test, the lack of extensive test data makes spot mode operation a key concern to SNP SMEs. The initial testing at 50 kW_e will likely not be sufficient to alleviate this concern. To mitigate this issue, SNP will initiate M&S efforts to identify alternate operating set points (e.g., mass flow rate and injection scheme) and nozzle designs that can reduce the probability of spot-mode operation. Controlled experiments during the 500 kW_e shakedown phase will be designed to bound "safe" operating conditions and at least one alternate anode design will be fabricated to be substituted if issues arise during testing.

- **Risk MPD-3**: There has been little extended testing of high-power MPD thrusters and essentially all testing to date has been performed with commercial laboratory supplies that are not representative of flight-like systems. SNP SME analysis of the modular 30 kW_e power processing technology (three 10 kW_e input modules) used for the ESEX arcjet flight (ref. [142]) indicates that this technology may be adaptable/scalable for MW_e-class MPD applications. Early efforts will be required to resurrect the ESEX technology and bench test high-power modules (∼100 kW_e) alone and in tandem. An SME team will also be employed to evaluate alternate components and design topologies. At least one alternative topology will be developed to the point that substitution would be possible in the TRL 4 testing sequence.
- **Risk MPD-4**: There has been little extended testing of high-power MPD thrusters and essentially all testing to date has been performed with commercial laboratory supplies in ballasted systems that provide marginal starting capabilities and are not suitable for space applications. High current transients at MPD startup are a major concern. Evaluation of starting transients will be a major focus in both the initial 100 kW_e testing (to be performed with COTS supplies) and at the outset of BB testing. Data on transient current-voltage characteristics will be provided to the PPU design effort and SNP will monitor the development (employing independent SMEs) on a regular basis as testing of a BB-fidelity unit (or units) proceeds and the BrB-fidelity design is developed and fabricated.
- **Risk MPD-5**: SNP-sponsored system/architecture modeling to date indicates that the anticipated thruster performance generated from past high-power MPD research and development thrusters (primarily the high power Russian testing (ref. [154, 230]) is sufficient to provide performance margin for the human Mars NEP application. The limited performance database is a cause for concern, however. Verification of thruster performance will be a major focus at the outset of BB testing in the shakedown phase. If performance is significantly lower than expected, MPD thrusters may not be a realistic option for this application. SNP plans to use an SME team to evaluate the early data and the thruster design for the ability to meet performance targets. Alternate operating conditions will be developed and employed if performance targets are not met in initial testing. These efforts will be coordinated closely with the design and operating regime efforts planned in addressing Risk MPD-2.

6.9 MPDT Maturation Summary

While they lack flight heritage at any power level, from an integrated system perspective Li-fed MPDT technology has significant advantages over competing propulsion technologies. Major advantages include:

- The ability to test at space-like vacuum levels in relatively modest, already existing ground testing facilities that require limited upgrades due to the ease with which the Li propellant can be condensed,

- A high-power density thruster that translates to system simplicity, low mass, and straightforward redundancy strategies,
- The potential availability of power processing technology based on flight heritage (ESEX) technology,
- Propellant storage as a low-pressure liquid in simple stainless-steel tanks, launching as a solid with the potential to mitigate launch vibration issues,
- Low pressure on-orbit propellant handing with technology for propellant feeding adapted from existing fusion research programs.

The major hurdles that must be addressed prior to selection of a thruster technology for a high power NEP mission are all associated with the required endurance capability of the thruster and its constituent components. For an MPDT, there is the potential that both cathode and anode erosion could present an issue limiting endurance. Promising technology advancements have been achieved over the last decade and implementing and validating these advancements is at the heart of the MPDT technology maturation plan. Clear milestones, documented risks and risk mitigation strategies, and NAR oversight are all specified in the maturation plan. As written, this plan will determine the efficacy of Li-fed MPDT systems for NEP missions and advance the readiness to TRL 5 during a time period of four years or less.

Chapter 7

Advancement Plan – CTE-5: Primary Heat Rejection Subsystem (PHRS)

The Primary Heat Rejection Subsystem (PHRS) is Critical Technology Element 5 (CTE-5) in the NEP system. During operation, critical PHRS functions are to 1) accept waste heat from the heat exchanger at the outlet or 'cold' side of the Power Conversion Subsystem (CTE-2), 2) transport the waste heat to a large set of radiator panels, and 3) radiatively reject that heat to space. The CTE-5 radiators are typically the largest single contributor to overall mass and size for a high power ($>$100 kW_e) NEP-based spacecraft, so optimization of the PHRS is a major consideration on the minimization of overall power system specific mass α. Recent assessments (see, for example, refs. [19, 20, 21, 22, 23, 24, 25, 26, 27]) indicate that the electric propulsion subsystem (CTE-4) for human-rated Mars-class missions will require power levels of at least 2 MW_e, and this requirement, combined with the reactor temperature and the power conversion efficiency, set a bound on the power that must be rejected by the radiators and determine the temperature range over which that rejection occurs.

CTE-5 only addresses the primary heat rejection for the power system. Beyond the PHRS for the power conversion thermodynamic cycle, there will be other, much smaller radiator assemblies for thermal management of power electronics or other subsystems for the spacecraft. While the specific configuration and location of these radiators will be dependent on the final subsystem and system design, SME review indicates that existing technology will provide sufficient functionality to handle these smaller thermal loads. Thus, the development of these radiators is categorized as straightforward engineering and not considered in this TMP.

For perspective, Figure 7.1 shows the ISS next to an engineering concept design of a 2 MW_e NEP/chemical propulsion spacecraft with a total primary radiator area of approximately 2,500 m^2. (ref. [25]) At 160 m^2, the ISS radiator system (panels indicated in the figure) is the largest ever flown. The projected NEP PHRS size requirement is more than an order of magnitude larger than the panels on ISS (ref. [231]). For comparison, the 100 kW_e-class ISS solar array panel area is 2,500 m^2, which is comparable to the projected NEP radiator size. The ISS solar arrays were delivered individually and attached to the truss using spacewalks and the ISS robotic arm – a clear demonstration of the feasibility of in-space assembly of complex structures. SNP development efforts will consider both conventional deployable radiator panels and options for the launch and subsequent in-space assembly of the array from individual components, such as radiator panels, truss components, and tubing. Further, extensive work on advanced passive thermal control has been performed and will be considered (ref. [232]).

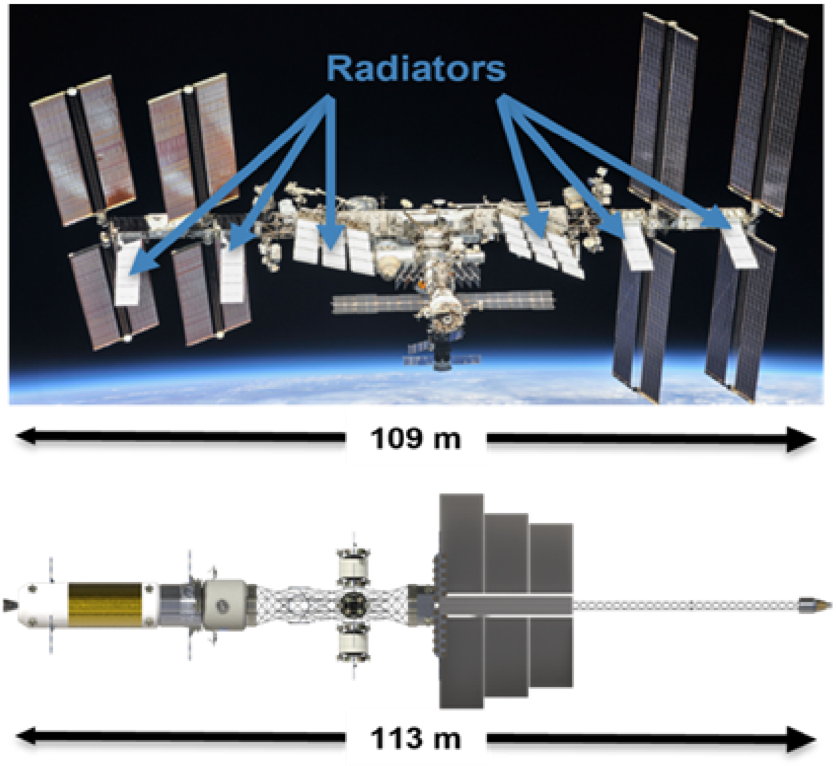


Figure 7.1: Comparison of ISS (top) and a conceptual design of a human-rated, 2 MW_e-class NEP/Chemical spacecraft (bottom) for perspective.

For the planned SNP technology development efforts, the PHRS is subdivided into three MAs. These are:

- **MA1**: A high-temperature trunkline to transport heat from the PCS/PHRS heat exchanger at the CTE-2/CTE-3 interface to the radiators. MA1 includes all hardware required to pump the working fluid in the trunkline. The pumping hardware may be either mechanical or electromagnetic, as discussed below.
- **MA2**: A large array of modular radiator panels for heat rejection, connected to the hightemperature trunkline via trunkline heat exchangers.
- **MA3**: The associated support hardware required to efficiently transport heat from the PCS/PHRS heat exchanger, along the trunkline, and out to the radiator panels for rejection to space. MA3 support hardware includes, but is not limited to, valving, ballasts, connectors, secondary heat exchangers, temperature sensors, and flexible joints, it also includes the structures required to support system deployment and maintain structural integrity in the space environment. This structure could be subjected to

significant loads during the course of a mission when the chemical propulsion system is operated.

All CTE-5 advancement efforts center on completing the focused research and development required to bring PHRS hardware to technical maturity at the sizes, flow rates, and temperatures necessary to support credible consideration for use in completing a range of human Mars missions. The PHRS development strategy is based on three major considerations:

1. Multiple potential assembly and deployment options exist. Rapid advancements are being achieved for both launch vehicles (LV) and in-space servicing, assembly, and manufacturing (ISAM). The LV market trends are well known, with several operational or soon-to-beoperational commercial options (e.g., Falcon 9, Starship, New Glenn, Vulcan). One of the technical interchange meetings on NEP hosted by SNP was focused on leveraging work from the ISAM community (ref. [30]) for the purpose of using in-space construction and assembly techniques to design an interplanetary vehicle optimized to perform the intended mission as opposed to pursuing a traditional constrained design that was packaged to fit within launch vehicle fairings and would require mechanisms to unfold and deploy in a series of steps prior to reaching a final configuration.
2. The PHRS itself is an integrated subsystem, where performance implications of design choices for MA1, MA2, and MA3 are interconnected. As such, assessments of the effects of different design options on the system mass and overall system performance will be performed throughout the maturation process.
3. Radiator panel performance depends on the combination of three radiator surface characteristics – thermal emissivity in the IR for heat rejection, solar absorptance to account for solar heat input in the UV/visible spectrum, and IR absorptance to account for heat input from planetary albedo (ref. [232]). Contributions from each of these factors must be considered in radiator surface development and are configuration and flight profile dependent. For example, a spacecraft designed with a planar bi-wing configuration flown edge-on to the sun minimizes solar flux and greatly reduces the need for a radiator surface with low solar absorptivity. Three-dimensional (tri- or quad-wing) array configurations may be hampered both by the solar absorptivity of the panels and panel-to-panel view factors. A recent SNPsponsored study showed that a bi-wing radiator flown edge-on to the sun results in a 30-40% mass advantage when compared to tri-wing options (ref. [231]). The low maturity of surface treatments that provide both high emissivity and low solar absorptivity in the temperature range of interest may be a major system and flight profile driver for high-power NEP missions.

The NESC assessment (ref. [28]) indicated that all key PHRS technologies are at AD^2 levels that suggest a prudent strategy to development and maturation is the pursuit of multiple parallel-path options for each key functionality (specifically, heat transport and heat rejection). SME evaluation has allowed for the selection of specific technologies as points-of-departure in maturing CTE-5.

The heat exchanger at the CTE-2/CTE-5 interface is contained in CTE-2, leaving the transport of heat from this heat exchanger to the radiator panels completely within CTE-5. While HPs have been considered for heat transport trunklines (refs. [67, 232, 233, 234]), SME reviews of past and recent studies (refs. [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 68, 231, 234, 235]) and the information gathered in the PHRS TIM (ref. [30]), along with additional individual technical discussions with external experts, led to the recommendation to select a pumped liquid metal system as the primary path for the trunklines. Pumped liquid metal trunklines have been demonstrated in nuclear systems using a variety of working fluids – most notably mercury (Hg), NaK, and Na (refs. [234, 236, 237]). Based on an assessment of the SOA, the basic trunkline component materials (for manifolds, connectors, etc.) and manufacturing technologies are relatively mature requiring only relatively straightforward engineering development for BB and BrB development. Consequently, the trunkline itself is not considered a major focus of CTE-5.

The technology readiness of all potential pump candidates for the CTE-5 trunkline is low. The low technology readiness necessitates the evaluation of multiple potential pump technology candidates for the CTE-5 trunkline, and development and demonstration of the pump will be a major focus of MA1 advancement efforts. Mechanical pumps were successfully developed for early NEP systems with the most notable example being the SNAP-8 NaK pump and other 1960s Hg pumps (ref. [238]). More recently, mechanical pump development was revived for programs such as fission surface power (FSP) (ref. [239]) and mechanical pumps are a strong candidate for development. Electromagnetic pump (EM pump) technology has been the subject of multiple development efforts (ref. [240]) and are carried as an alternate development path with a projected down selection (MP versus EM pump) anticipated at the TRL 4 advancement milestone.

Like liquid metal pump technology, heat rejection candidate technologies ranging from simple HP or pumped liquid metal radiator panels (to be discussed later in detail) to more exotic radiator concepts such as liquid-drop radiators, moving-belt radiators, etc., (ref. [241]) have been considered for use in MA2. Based on extensive reviews of past and ongoing research, it is anticipated that the PHRS will employ either large radiator panels based on carbon-composite radiator fins with embedded HPs or radiators based on emerging oscillating heat pipe (OHP) technology. The latter is presently at a lower state of technology readiness compared to conventional HPs, but it has experienced rapid development for programs such as FSP and may offer significant performance benefits in terms of heat transfer rate, operating temperature range, and specific mass. Focused research on manufacturing (e.g., brazing), fluid choice optimization, and performance scaling will all be required prior to selection for an NEP system. For conventional HP configurations, the exact fin technology, panel coatings, HP construction, thermal bonding techniques, and working fluid are yet to be determined, but significant technology development has been performed over the past 4 decades and advancement is considered relatively straightforward. Relevant HP technologies are discussed later in this section.

A simplified block diagram of the CTE-5 subsystem is shown in Figure 7.2. The primary heat exchanger resides on the CTE-2 side of the CTE-2/CTE-5 interface. As shown, hot liquid metal from the interface inlet is pumped along a main trunk line, encountering heat exchangers at the root of the radiators where the bulk of the heat is extracted from the flow, leaving “cooler” liquid metal to return to the CTE-5/CTE-2 heat exchanger interface. The liquid metal pump is shown on the "cool" side of the trunkline (as it is in the SNP system model), but a decision on this location will be evaluated upon program initiation. A single radiator panel type, replicated N times, is shown. In the implementation phase, a second set of radiators of a different design may be incorporated in series if the temperature level and thermal profile necessitate the use of two different designs or working fluids. Similarly, a mixing assembly may be added to moderate the liquid metal temperature in the trunkline to permit the use of a single radiator type. Additional components like temperature sensors and accumulators will be used as required. SNP SME assessments indicate that anticipated heat exchanger, accumulator, temperature sensor, and valve requirements can be met through straightforward engineering application of existing technologies. As an example, a survey of motor-controlled globe valves (ref. [242]) included a high temperature valve used in liquid Na reactor loops (higher temperature/much larger cycle requirements/harsher environment than needed for CTE-5). Such a valve should be adaptable to meet any bypass valve requirement in the NEP CTE-5 system through straightforward engineering development efforts. If there is a heat exchanger for the interface between CTE-1 and CTE-2, that component will require a much higher temperature capability than the CTE-2 to CTE-5 heat exchanger. Consequently, the former will require significantly more maturation relative to the latter.

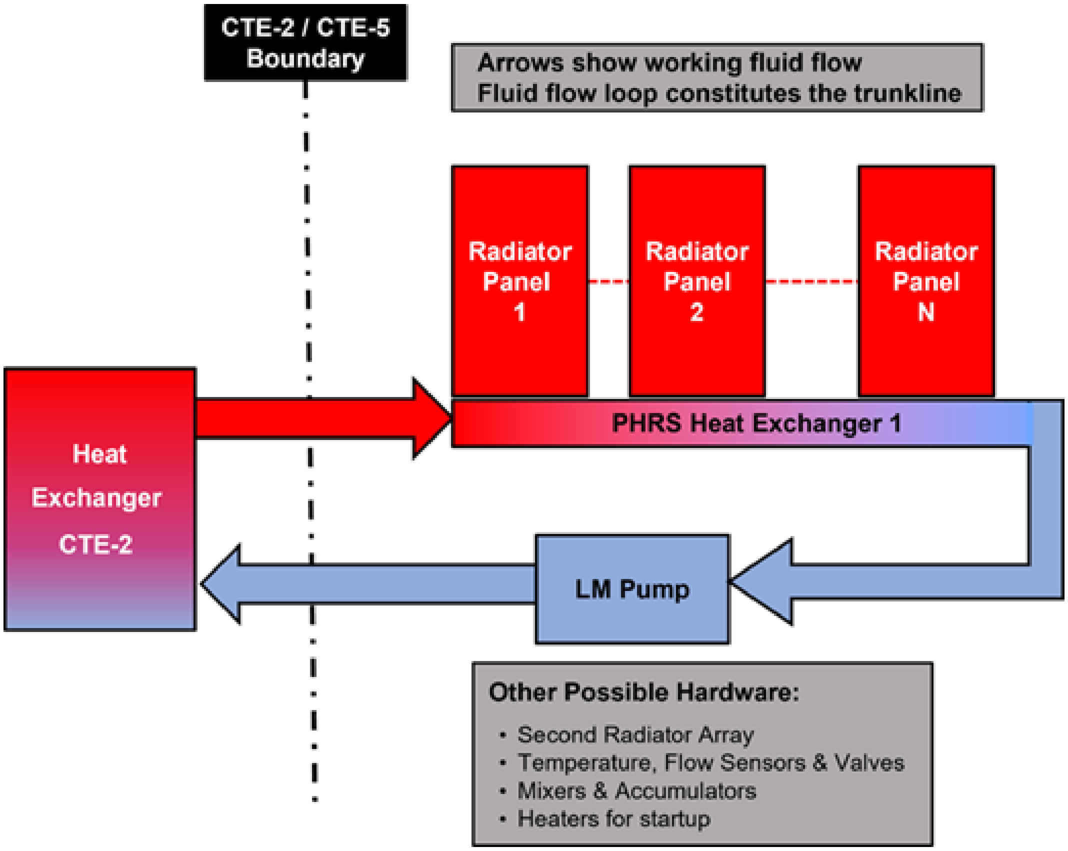


Figure 7.2: Simplified block diagram of the PHRS.

In keeping with the robust SE&I philosophy described in the Introduction, a detailed Interface Description Document (IDD) will be developed for the external CTE-2/CTE-5 interface. Preliminary descriptions of this interface are discussed in this section, but a stand-alone IDD will be developed by SNP SMEs and provided to the SNP CTE-5 lead after discussion at the opening workshop. This IDD will be reviewed by SNP, circulated for SME evaluation if required, and then finalized and kept by the SNP SE&I lead. The document will be reviewed and revised as needed at each major relevant milestone, including as part of the NARs planned for technology advancement verification with NAR approval of the IDD as a condition for advancement.

In addition, IDD's will be generated for each MA-to-MA interface to ensure compatibility as the PHRS breadboard and brassboard development efforts progress. These CTE-5 internal IDDs will be maintained by the CTE lead and reviewed with the SNP SE&I lead and/or SMEs as needed. All applicable standards, including those required for human rating, will be identified at the opening workshop and applied as appropriate so the brassboard hardware developed to achieve TRL 5 will translate to TRL 6/prototype/flight-like designs without requiring any appreciable additional research and maturation. For example, applicable requirements from NASA's SMC-S-010 Technical Requirements for Electronic Parts, Materials, and Processes used in Spacecraft will be used to identify the key features of all components (e.g., valves and switches) and material (e.g., heat pipe, radiator, coating) technologies needed to make these technologies either directly applicable or easily evolvable to flight-quality hardware via standard engineering practices. NAR validation of this extensibility will also be a condition for technology advancement. Additionally, at the TRL 4 and TRL 5 NAR reviews, the latest CTE-5 technology status will be combined with the latest results from the development of all the other CTEs and incorporated into a continuously-evolving conceptual vehicle configuration assessment to ensure that the combined CTEs will lead to a feasible and practical vehicle configuration.

System level modeling conducted in conjunction with technology maturation planning to date has identified KPPs for the various CTEs. The flight PHRS KPPs will depend on further detailed system-level trades, which require high fidelity inputs for performance and subsystem mass acquired during the process of technology maturation to TRL 4 and TRL 5. The preliminary KPPs shown in Table 7.1 were developed via an iterative process between SMEs and an SNP modeling team working to set the targets for focused hardware development efforts. As the iterative design process evolves during the execution of this TMP, important parameters such as (for example) the inlet and outlet temperatures may change based on specific system design aspects that are still under consideration (e.g., inclusion of a recuperator or multiple stages in CTE-2). This uncertainty should not, however, have a major impact on the technology advancement goals for the PHRS. The development of an efficient, long-life liquid metal pump and the demonstration of manufacturing, assembly, and deployment for large, lightweight, interconnectible radiator panels will be required for technology maturation irrespective of initial uncertainties in system KPPs.

Table 7.1: KPP Guidance for CTE-5 Technology Development Targets.

KPP	**Threshold**	**Target**	**Significance**
Mass per Area of Panels & Transport ($\mathrm{kg/m^2}$)	4.5	3.0	Primary heat rejection assembly mass without system-specific structure.
Mass per Area of Primary Boom Structure ($\mathrm{kg/m^2}$)	2	1	Structural mass (scales with heat rejection assembly mass and CTE-1 mass).
Total Power Radiated ($\mathrm{MW_{th}}/\mathrm{MW_e}$)	1.5-3		Assumes power conversion efficiency range (25-40%) consistent with CTE-2 KPP range with 1.5-3 $\mathrm{MW_{th}}$ to dissipate (3 – 12 $\mathrm{MW_{th}}$ total) per $\mathrm{MW_e}$ generated.
End-of-Life Emissivity	0.85	0.9	End-of-Life emissivity of radiator panels.
CTE-5 Outlet Temperature (K)	320-450		Cold-side trunkline return; Encompasses the range of outlet temperature expected to minimize system α balanced with limiting radiator area given the PCIT KPP; corresponds to CIT KPP.
CTE-5 Inlet Temperature (K)	550-750		Hot-side trunkline inlet; Encompasses the range of CTE interface temperatures expected to minimize system α or radiator area given the PCIT KPP range.
Lifetime (Years)	3	10	3 years provides margin for single (2.5 year) human mission to Mars, 10 years enables multi-trip reuse

SNP's milestone-driven approach is focused on hardware demonstration in relevant environments in combination with development of a suite of comprehensive, predictive physical models to mature technologies to TRL 5 in the timeframe of interest. As with all other CTEs, all TRL and AD2 advancement will be independently verified through the use of NAR.

For the planned focused research and development efforts, SNP has developed the CTE-5 WBS shown in Figure 7.3. While the various technology selections (e.g., radiator and pump designs) will influence the advancement activities in each WBS element, the required elements are, in general, not dependent on the selection of specific technologies.

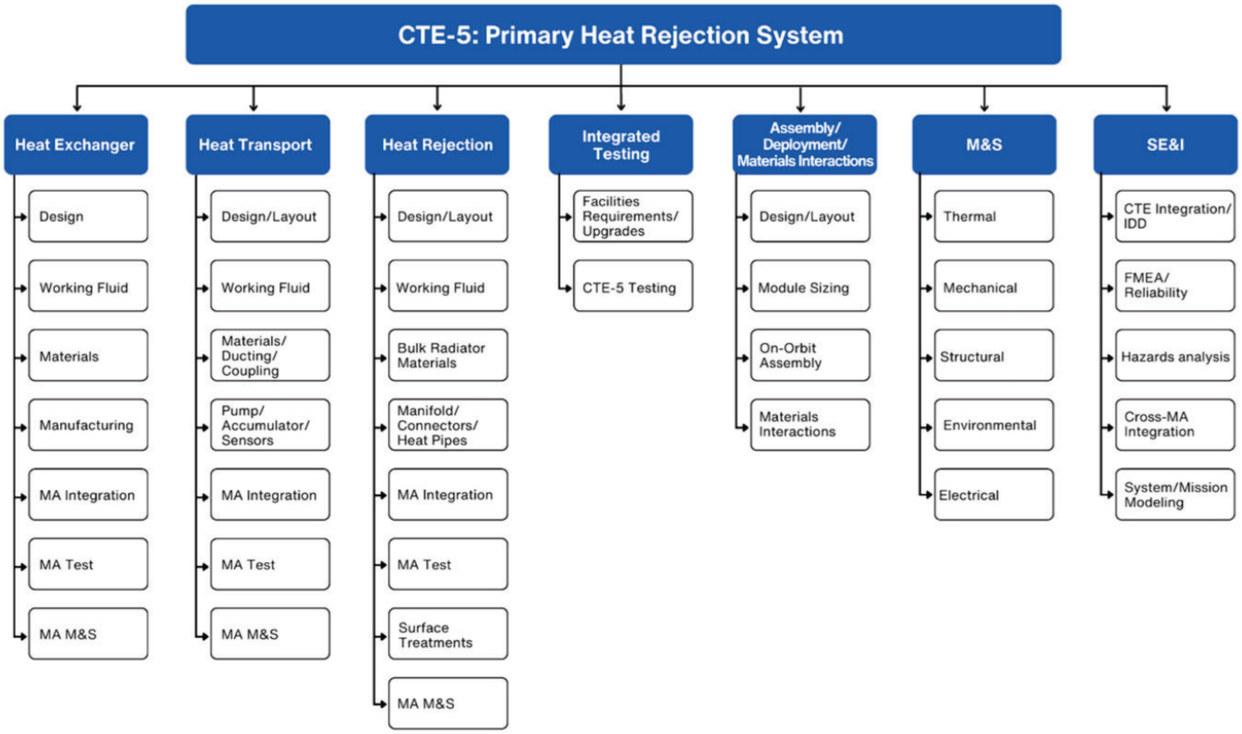


Figure 7.3: WBS for PHRS subsystem development management.

The balance of this chapter describes 1) the background, SOA, and the technology gaps associated with MA1 and MA2 technology advancement, 2) milestone-driven technology maturation schedules, and 3) a preliminary assessment of major risks and risk mitigation strategies.

When discussing failure modes and hazards, both exogenous hazards to the spacecraft (e.g., micrometeorite strikes and radiation on the radiator panels) and physical hazards will be considered. A preliminary list of these will be generated by SNP SMEs and refined as the development efforts progress. Necessary activities to mitigate exogenous hazards will be included under the appropriate technology development effort shown in the WBS (Figure 7.3). Models will be developed to understand failure modes and environments requirements (including, for example, radiation hazards), and the quantification of their impacts on the design. Tracking of advancements to address and mitigate these issues will be carried under the "Environments" and/or "FMEA development" boxes in the WBS. Safety hazards, such as the inherent danger of pumping high temperature liquid metals, will be addressed as part of NASA's standard Safety and Mission Assurance processes.

7.1 PHRS Background, SOA, and Technology Gaps

Early satellites relied on passive, solid radiators with conduction-dominated heat transfer. As heat rejection requirements increased due to greater on-board power levels or environmentally generated heat loads, passive systems become insufficient and HPs and/or liquid metal systems employing more complex radiator assemblies and high-emissivity coatings were required. The Parker Solar Probe radiator system, for example, employs aluminum (Al) radiator fins with embedded titanium (Ti) HPs using pressurized water as the working fluid (refs. [243, 244]). As another example, the External Active Thermal Control System (EATCS) on ISS is the largest operational heat rejection system in space with a total area of approximately 160 m^2 and a nominal heat rejection capability of 70 kW_{th} (ref. [245]). The total ISS subsystem employs individual honeycombed Al panels in multiple panel assemblies, with heat transported to the panels using an embedded pumped-loop system with anhydrous ammonia as the working fluid. The ISS panels have a Z93P white coating on the radiator panel surfaces (ref. [246]), increasing the surface emissivity while maintaining low solar absorptivity and minimizing the required radiator area. One ISS panel assembly is shown in Figure 7.4 during development testing at a Lockheed Martin Missile and Fire Control facility.

Figure 7.4: Deployed ISS pumped ammonia based PHRS panel assembly.

While the ISS PHRS provides many lessons learned for the design and deployment of large radiator systems, the physical properties of the aluminum panel material, the ammonia working fluid, and the coating are all not suitable for the anticipated temperature ranges in NEP applications (at any power level).

Major Assembly 1 – Trunkline: Most NEP spacecraft and mission analyses have focused on dual fluid PHRS systems with MA1 employing a pumped liquid metal approach to conduct the heat load from the outlet of the PCS to the MA2 radiators, which subsequently employ embedded HP-based panels that are designed to effectively spread the heat across the panel surfaces for rejection to space. liquid metal heat transport systems that operate at temperatures from 1,000 K to more than 1,500 K are commonly used to cool nuclear systems. Since the NEP radiators have a much lower inlet temperature range, as shown in Table 7.1, much of the technology associated with radiator trunkline fabrication can be considered sufficiently mature for this TMP. Multiple working fluids (e.g., pure alkali metals like Cs, Na, K, and eutectics like NaK, CsNaK) are well understood and are compatible (in the temperature range of interest) with trunklines fabricated from stainless steel or existing superalloy materials. NaK, for example, remains liquid at low pressure (∼1 atmosphere) over the temperature range of 261-1,033 K (ref. [247]). This spans the required range for NEP radiators (∼550-750 K – see Table 7.1, CTE-5 inlet temperature) with significant margin. The addition of Cs and/or K yields eutectic fluids with even wider operating ranges (ref. [247]). Although NaK is corrosive and pyrophoric, there is an established experience base for its use as a working fluid in high-temperature heat-transfer systems (ref. [247]). NaK-based eutectics were identified by SNP as the highest TRL option for the thermal trunkline working fluid (ref. [30]) and multiple recent studies have all selected a NaK-based trunkline delivery method as their baseline (see, for example, refs. [19, 20, 21, 22, 23, 24, 25, 26, 27]). It is noted that while water may be an optimal choice for radiator operation (see section on MA2, below), it is undesirable as a working fluid for a trunkline, which would require supercritical water at pressures greater than 20 MPa. Water also has a positive coefficient of thermal expansion at low temperatures so design employing water must avoid situations in which freezing could occur (e.g., during possible cold soak). Using ammonia, the working fluid on ISS, would still require supercritical operation at pressures exceeding 11 MPa.

Recent relevant trunkline technologies were developed as part of the ongoing NASA FSP effort (ref. [236, 240, 248]). Extensive past work employed a laboratory model 10 kW$_e$ technology demonstration unit (TDU) with a NaK-based pumped loop assembly. This unit was operated in 2016 in Vacuum Facility 6 (VF-6) at GRC (ref. [236]) using a simulated nuclear heat source. A picture of the TDU installed in the chamber is shown in Figure 7.5. In that test, the pumped NaK extracted heat directly from the electrically heated reactor simulator and delivered that heat to Stirling power conversion units at a nominal NaK fluid temperature of 875 K. This temperature is significantly higher than the anticipated requirement for the NEP PHRS trunkline.

Gallium (Ga)-based liquid metal eutectic alloys, such as Galinstan, may also deserve consideration as a working fluid for the thermal trunkline (ref. [247, 249]). The Galinstan eutectic has a wider liquidus range than NaK, providing more flexibility for optimization of the CTE-2/CTE-5 interface. Although more expensive than NaK, Ga-based alloys are much less hazardous and easier to handle, which might result in lower overall development costs. Against that, they have lower thermal conductivity than NaK, and there is little to no experience with their use as a coolant. There may also be unknown materials compatibility

Figure 7.5: FSP TDU installed in Vacuum Facility 6 at NASA GRC.

issues that would require focused research and development. Gallium-eutectic-based systems are clearly at a lower stage of technical maturity compared to NaK and pure Na, warranting SME evaluation in early stages of MA1 formulation before proceeding with development work on a Ga alloy-based system.

Overall, the SOA for the liquid metal trunk line is based upon work performed for operational reactor systems employing liquid metal coolants, ranging from NaK at the low end of the temperature range to lead bismuth (Pb-Bi) eutectic mixtures at the high end (well above 1500 K [ref. [247]]). Consequently, the trunk line, with the exception of the technology required to pump the working fluid, may be considered straightforward engineering in the high-power NEP application.

Major Assembly 1 – Liquid Metal Pumps: Unlike the anticipated trunkline manifolds, liquid metal pumps at the sizes required for an NEP application and with the capability to operate in the space environment are at a low state of technical maturity and require significant focused research and maturation. Estimates from SNP's most recent modeling indicate that for a NaK78 working fluid, the pumping assembly will be required to support a mass flow rate of approximately 30 kg/s at temperatures up to 750 K for the duration of the mission.

Liquid metal pumps fall into two broad categories, mechanical pumps and electromagnetic pumps (EM pumps). From the standpoint of demonstrated performance in a realistic system, the mechanical pump developed and demonstrated under the SNAP-8 program in the 1960s came the closest to meeting NEP requirements for throughput and operational lifetime. The SNAP-8 reactor was designed to operate at 35 kW_e with a coolant system employing two mechanical pumps in the configuration shown in Figure 7.6.

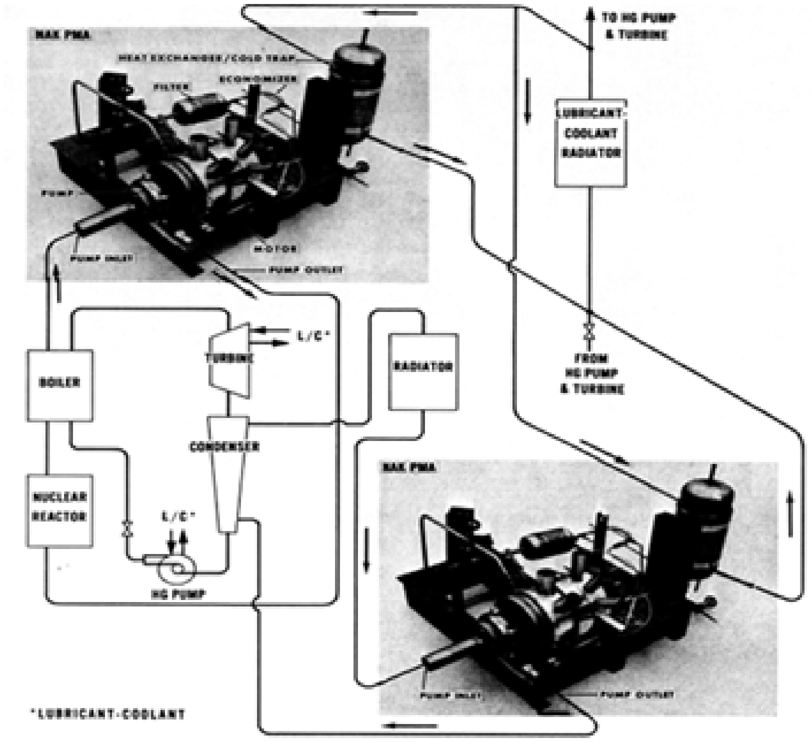


Figure 7.6: Schematic of the NaK pump motors in the SNAP-8 system (Aerojet-General).

These mechanical pumps were developed by the Aerojet-General Corporation under the SNAP-8 program (ref. [250]). A focus of this development was the engineering required for a NaK78-based reactor coolant system. The system had a nominal operating temperature of approximately 900 K – significantly higher than what is projected for the present NEP MA1 PHRS inlet temperature range. Multiple pumps were demonstrated, collectively, for more than 30,000 hours. One pump operated for over 10,000 hours – within a factor of 2 or 3 of the present NEP requirement. More than 700 cycles were accumulated – a cycling capability far beyond the projected requirements for the current NEP system – and typical flow rates were roughly 5 kg/s, which is within an order of magnitude of the NEP requirement. The SNAP-8 program employed technologies available in the early 1960s (materials, component design, fabrication, cooling techniques, etc.). The design was well-documented and post-test inspection indicated minor wear that could be addressed to eliminate essentially all known and observed life-limiting wear mechanisms. More recently (2010 timeframe), NASA developed and fabricated (but never tested) a mechanical pump for the FSP application using commercially available components modified for use with NaK (refs. [239, 251]). Mechanical pumps using ceramic components have been proposed for use with liquid metals and limited recent work has demonstrated continuous pumping of liquid tin (Sn) at temperatures of 1,670 K (ref. [252]) – well in excess of the NEP PHRS requirement.

EM pumps drive current in the working fluid, which interacts with a perpendicular magnetic field to generate a Lorentz ($\mathbf{j}\times\mathbf{B}$) body force that increases the pressure head and drives the required flow (ref. [240, 248]). These pumps fall into two categories – conductive (DC or AC current driven directly into the fluid through electrodes, which interact with an applied magnetic field) and inductive (oscillating external currents imposing a time-varying magnetic field that both generates current in the working fluid through Faraday's law and self-interacts with that generated current to produce an electromagnetic pumping force). EM pumps are attractive because they have no moving parts and can be 5 to 10 times smaller than mechanical devices. Of the conductive varieties, a thermoelectric-electromagnetic (TEM) conduction pump (shown in Figure 7.7) was used to drive coolant through the reactor in the SNAP-10A reactor in 1965 (ref. [253]). A scaled-up version of this technology was also considered for the SP-100 program in the early 1990s, but that pump was never fabricated or tested (ref. [254]). This type of EM pump was also considered for Project Prometheus (refs. [16, 17]). TEM EM pumps are attractive because the electric power required for operation can be generated from scavenged heat in the liquid metal via the thermoelectric Seebeck effect (ref. [253]).

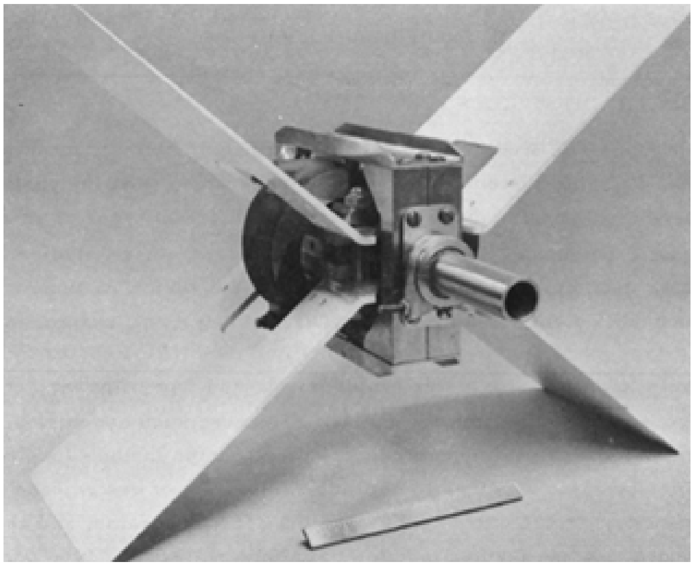


Figure 7.7: TEM NaK pump developed for the SNAP-10A reactor.

In the inductive category, recent space nuclear development focused on annular linear induction pumps (ALIP). This type of pump has served as the baseline in many NEP architecture studies (refs. [20, 21, 22, 25]) and FSP designs (ref. [238]). Relevant ALIP technologies were fabricated in support of NASA's FSP efforts (refs. [240, 248]). A pump was scaled for operation in a 10 kW_e FSP TDU where NaK at ∼800 K was the working fluid. The flow rate in this unit was approximately 2 kg/s, which is roughly an order of magnitude below the requirement for the NEP PHRS of this TMP. The pump is shown integrated into the FSP TDU in Figure 7.5. The same pump was more recently used in the testing of the Kilopower Reactor Using Stirling TechnologY (KRUSTY) (ref. [53]).

A simplified diagram showing the basic design of an ALIP, a photograph of the FSP TDU ALIP, and a schematic of the test loop employed to quantify ALIP pump performance are presented in Figure 7.8. Unfortunately, while simple in design and straightforward to analyze with respect to fundamental physics, recent iterations of the ALIP performed poorly with typical demonstrated efficiencies in the 4-6% range while operating under the conditions of interest (ref. [238]).

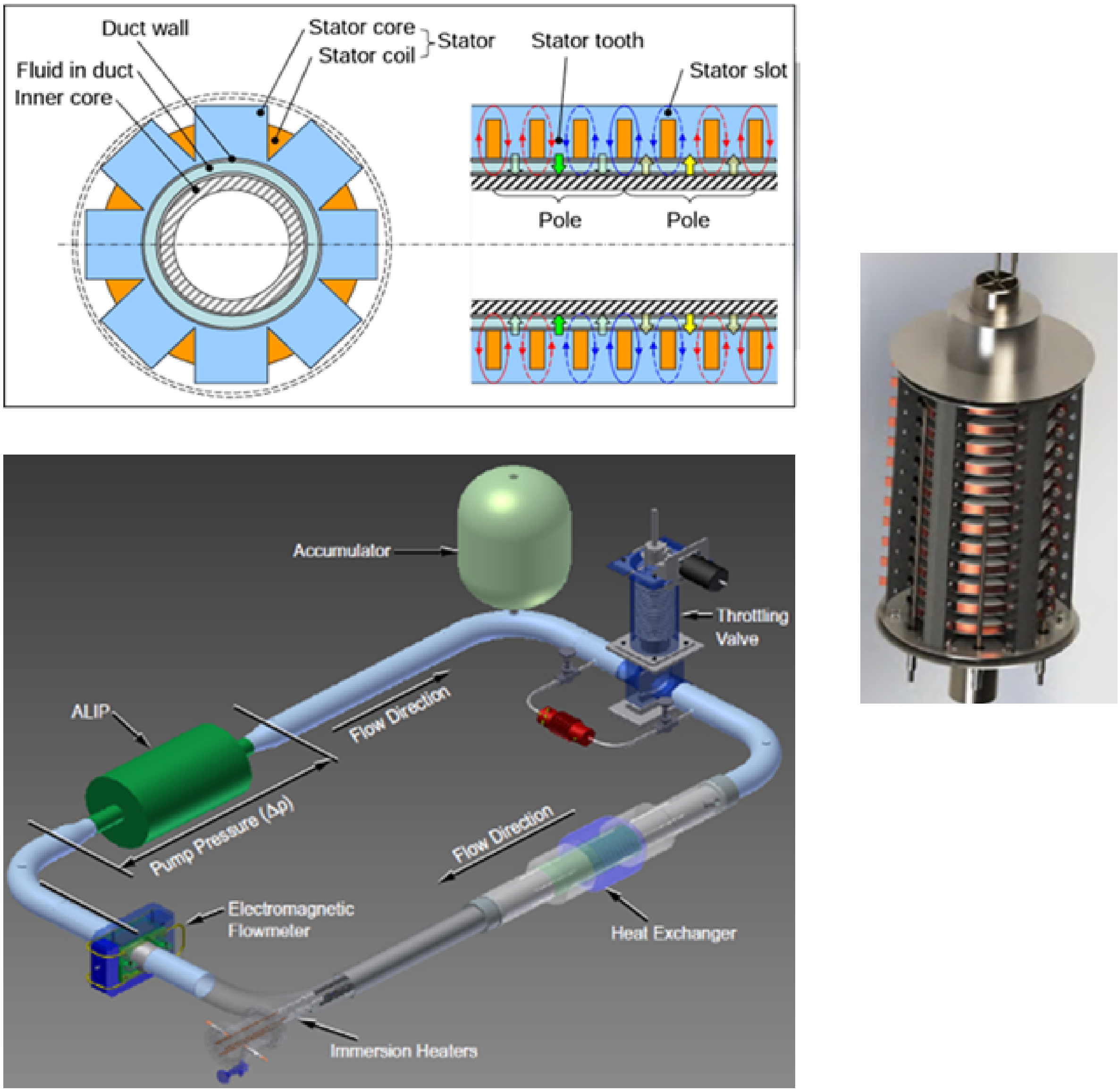


Figure 7.8: Clockwise from top-left, a simplified diagram of an ALIP, the FSP TDU ALIP, and a rendering of the test loop used to quantify EM pump performance.

Multiple studies have uncovered potential causes for low efficiency in this particular ALIP and point to design improvements that could increase performance (refs. [254, 255]), but as of this writing further development in this area has not been pursued. EM pumps are also used for various industrial purposes. Figure 7.9 shows, for example, a commercially available CMI Novacast pump used for pumping liquid Al for casting processes. This pump operates at temperatures up to 1,073 K, driving fluid at a mass flow rate of 10 kg/s, and drawing 14 kW_e of power (ref. [256]).

Figure 7.9: CMI Novacast PG450 Liquid-Metal Pump.

EM pumps are being developed by the US nuclear industry for both commercial and military applications, but the design and performance data for those pumps are mostly proprietary (ref. [30]). High-capacity ALIP pumps are also being developed internationally for large scale Na-cooled fast reactor systems (ref. [257]).

Technology gaps for NEP radiator trunklines are shown in Table 7.2. The main area of projected focus is pump development. The working fluid (once selected), trunkline materials, etc., require straightforward engineering and will be matured during the development of BB and BrB-fidelity assemblies fabricated in the course of the planned advancement activities.

Table 7.2: Major PRHS Trunkline Technology Gaps and Advancement Requirements.

	Technology	**Gaps and Advancement Descriptions**
1	Pumps	Current liquid metal pump technology is insufficient to meet NEP requirements (flow rate, temperature, lifetime, mass). SOA mechanical pump and EM pump technologies require thorough evaluation followed by a selection of a primary pump implementation with a backup option for risk reduction.

Table 7.2: Major PRHS Trunkline Technology Gaps and Advancement Requirements.

	Technology	Gaps and Advancement Descriptions
2	Working Fluid	NaK and other liquid metal options like Na and Cs have an extensive history of operation under conditions significantly harsher (i.e., as reactor coolant loops) than those required for the CTE-5 subsystem. Other candidates, such as galinstan, have been identified and require consideration. A selection is required at the outset of the program, with the expectation that existing technology can be employed to support focused BB and BrB-fidelity pump development. Development efforts must account for all operational environments and conditions (e.g., cold soak, radiation).
3	Ducting & Connectors	Ducting materials compatible with the liquid metal coolant exist but engineering efforts are required to design and fabricate the hardware required for the planned research and development. Connector technology is somewhat architecture dependent. A high temperature connector development effort (coordinated with the ISAM community and possibly involving in-space joining and assembly) is required.

Major Assembly 2 – Radiator Array: The radiator assembly receives the waste heat from the thermal trunkline and rejects it to space. Technical maturity and SME assessment indicates that the traditional finned radiator with center-attached heat transportation is the most mature technology and the most likely candidate for the first large-scale NEP application. Many more exotic concepts based on moving belts, liquid droplets, Curie point property differentials, and rotating bubble membranes promise to provide low α (refs. [30, 239]). These were evaluated by SNP SMEs, and it was determined that their technical maturity levels were too low for inclusion in the present TMP.

There are numerous possible heat delivery methods and numerous fin and coating material combinations that can be considered. In general, these combinations fall into two categories – active, with liquid metal pumped directly to the panels from the central trunkline thermal conductor, and passive, with HPs running along the panels and thermally connected to the trunkline through heat exchangers. While the active approach may appear to be the simplest, as it eliminates heat exchangers and a separate fluid transfer system, there are multiple potential drawbacks. The most important is the vulnerability of such a configuration to catastrophic micrometeoroid and orbital debris (MMOD) damage (ref. [239]). Micro-meteoroid puncture of a fluid loop in a radiator panel would lead to loss of all fluid in that panel and the consequent loss of the radiator surface for heat rejection, so damage tolerance is a primary concern. However, if fluid from the trunkline was directly pumped into all the radiators, a puncture of one panel could result in the loss of the entire heat rejection system. On the assembly level, a serpentine set of pumped fluid loops sourced from the trunkline would present additional pressure losses relative to the losses imposed by pumping the working fluid only in the trunkline. This would certainly affect the pumping requirements for CTE-5. Finally, deployment of an active system requires liquid metal connections and/or flexible ducts that are presently at a low level of maturity. Owing to these issues, the use of HPs as the central component for heat distribution to the radiator panels has become the preferred option in the space nuclear community (ref. [30]) and SNP SME assessments have yielded multiple technical reasons why HP-based finned radiators are the technology of choice for an NEP system. An MMOD strike, for example, may damage a single HP, but such an event would not be catastrophic to the operation of the overall PHRS subsystem since there is no intermixing of fluids between the trunk line and the HPs at the heat exchanger interface. Furthermore, the heat exchanger required for thermal contact with passive radiators is much less of a technical challenge than the heat exchangers for the CTE-1/CTE-2 or CTE-2/CTE-5 interfaces, and any technology maturation efforts pursued to advance those heat exchangers would be directly applicable to the interface between the radiator HPs and the trunkline.

Working Fluid: There are many different types of HPs with variations depending upon the conductance method chosen (constant, variable, other), the working fluid type, the tube material, and which wick approach is employed (if a wick is used, at all). The selection of the working fluid is a major key to effective radiator operation – the HP must be operational over the temperature range of interest (including during off-nominal conditions like those encountered at startup) and must be compatible with local, subsystem, and system-level requirements. The radiators and PHRS must be designed to handle operation at both the radiator inlet (hot-side supply) and outlet (coldside return). The KPP temperature range for the cold-side return in the PHRS shown in Table 7.1. KPP Guidance for CTE-5 Technology Development Targets. is within the intermediate temperature range for water HPs. The temperature range shown for the PHRS inlet temperatures, on the other hand, are generally greater than the typical limit for traditional wicked water HPs (ref. [258, 259]).

Figure 7.10 shows the HP merit number M as a function of temperature for a number of working fluids. The merit number is defined as

$$M = \frac{\rho\sigma\lambda}{\mu}$$

where ρ is the fluid density, σ is the surface tension, λ is the latent heat of vaporization, and μ is the dynamic viscosity (ref. [256]). It has units of kg/s^3 and is a measure of the ability of a fluid to transport heat in an HP, with larger numbers representing greater heat transport capability.

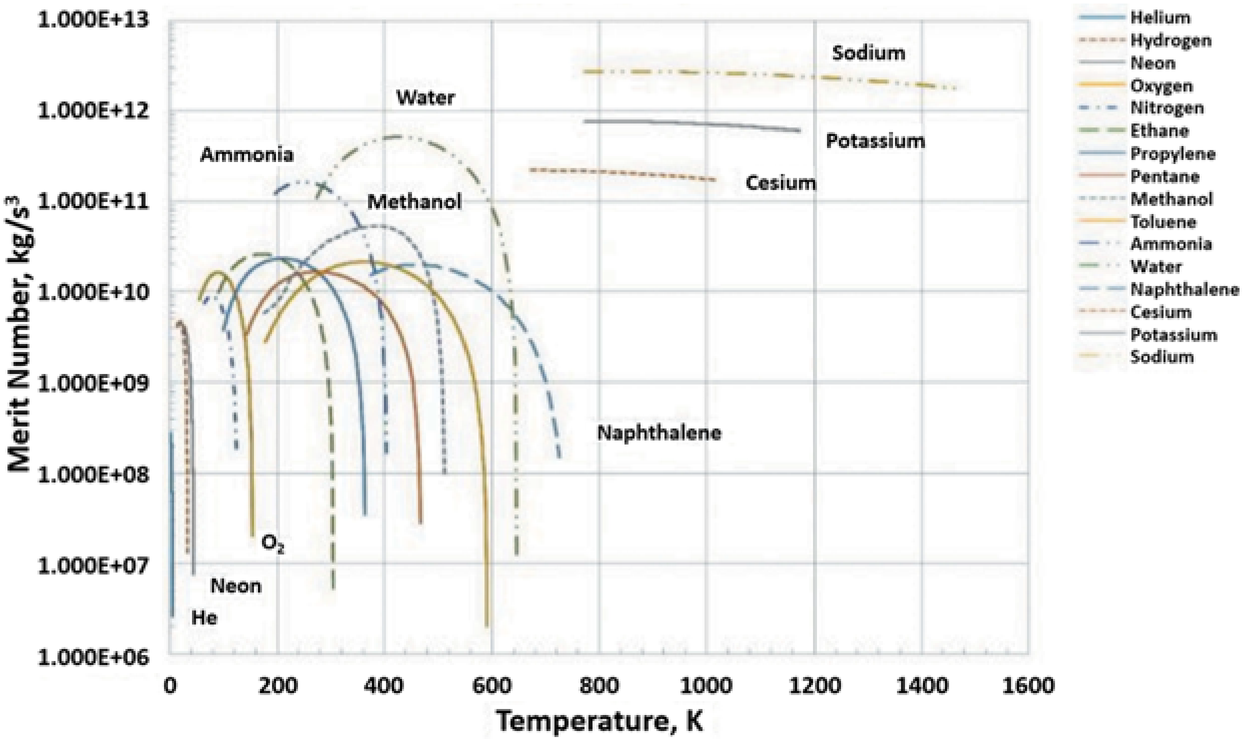
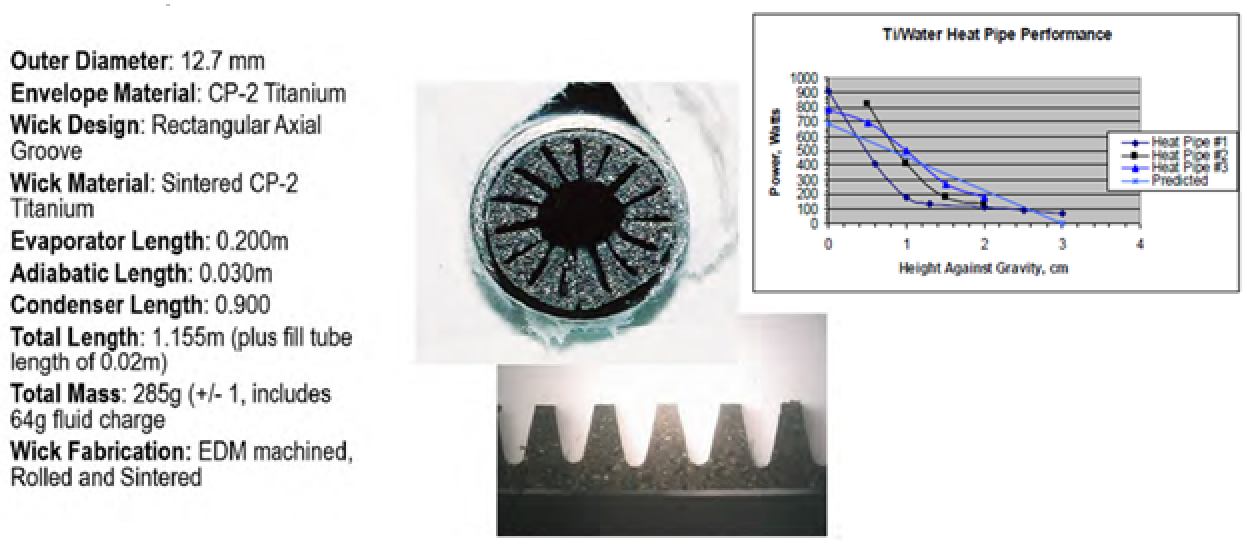


Figure 7.10: HP Merit Number M of Various Fluids as a Function of Temperature (ref. [257]).

For in-space applications, water has been a fluid of interest for decades and comprehensive research efforts have advanced water HP technology, making it potentially attractive for space nuclear applications (see for example, refs. [260, 261, 262]) can be seen from the figure, however, water begins to lose its effectiveness as a HP working fluid at temperatures above 500–550 K. Alkali metal HPs (Na and Cs in particular) have found common use at higher temperatures and have been used in systems operating at or above 700 K (refs. [263, 264, 265, 266, 267]). Unfortunately, these fluids are not useful at the lower end of the temperature range expected for CTE-5. Because no proven universal HP fluid exists, some combination of implementations may be required if, in fact, the optimal CTE-5 inlet temperature is greater than 550 K. In depth SME technology evaluations combined with the results of NEP system modeling will be used to determine the advantages and disadvantages of different HP design implementation strategies, including the use of multiple working fluids as a function of the trunkline temperature profile. The milestones and schedules shown in this TMP are representative of the tasks required for the advancement of a radiator panel employing a single HP working fluid. If it is determined that PHRS optimization on the system level requires the use of multiple HP fluids in the design, parallel and essentially identical technology advancement paths will be required for each HP fluid selected.

Water Heat Pipes: Most NEP and FSP HP development efforts to date have centered around the use of titanium (Ti) tubes with grooved wicks (example shown in Figure 7.11).



Outer Diameter: 12.7 mm
Envelope Material: CP-2 Titanium
Wick Design: Rectangular Axial Groove
Wick Material: Sintered CP-2 Titanium
Evaporator Length: 0.200m
Adiabatic Length: 0.030m
Condenser Length: 0.900
Total Length: 1.155m (plus fill tube length of 0.02m)
Total Mass: 285g (+/- 1, includes 64g fluid charge
Wick Fabrication: EDM machined, Rolled and Sintered

Figure 7.11: Ti/water HP Example from Project Prometheus (ref. [30, 259]).

The example shown is from the early 2000s-era Project Prometheus (refs. [30, 259]), which baselined a 100 kW_e-class closed Brayton cycle power conversion system with a pumped NaK thermal trunkline delivering heat to an array of carbon-carbon composite radiator panels. These panels used embedded Ti/water HPs for in-panel thermal transport. Heat transfer from the trunk to the radiator panels was to be achieved by embedding the evaporator section of the HPs directly into the NaK trunkline channels. While the Project Prometheus assembly was never fabricated, extensive Ti/water HP research was performed including side-by-side testing of hardware (see Figure 7.12) from multiple HP vendors.

Figure 7.12: Multi-vendor HP Comparison Testing Apparatus (Project Prometheus, ref. [17, 260]).

Project Prometheus contributions to technology maturation in this area include the development of an effective carbon-carbon panel-to-Ti tube brazing technique and early evaluations of epoxy bonding and graphite foam saddle materials (ref. [17]).

Water Heat Pipes/Finned Radiators: As with liquid metal pumps, many varieties of Ti/water HPs embedded in radiator fins have been developed. Most modern fins are based on fiber reinforced composite materials and range from the relatively complex single or multi-channel technology (ref. [261]) shown in Figure 7.13 (left) to simpler low-cost single layer/epoxy-bonded fins recently developed and demonstrated under the FSP program (ref. [262]). A generic schematic diagram of the joint between a HP and a fin is depicted in Figure 7.13 (right).

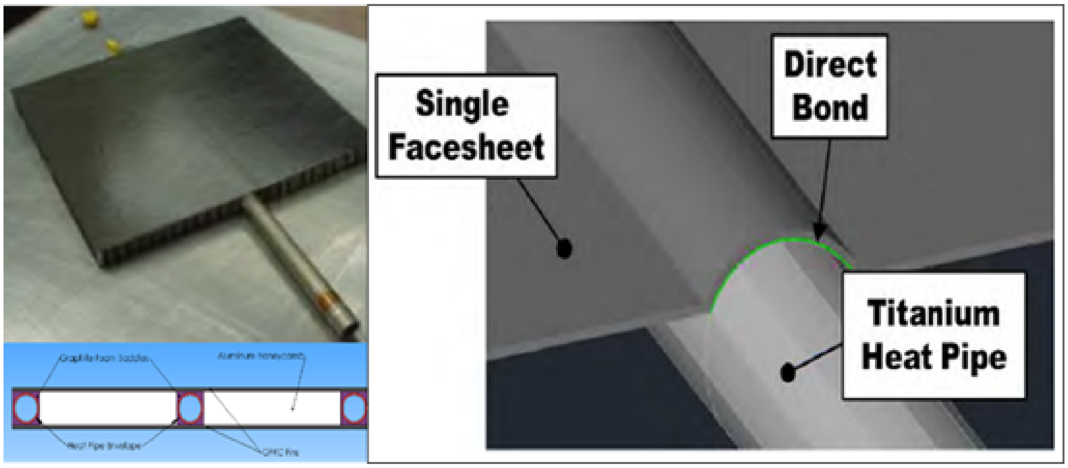


Figure 7.13: Sandwich and “Low-cost” Composite-based Radiator Examples.

Extensive research and development led to major demonstrations of these technologies beyond those of Project Prometheus. Panels of the former type were designed with polymer matrix composite (PMC) face sheets bonded to an aluminum honeycomb sub-structure. These used equally spaced Ti/water HPs running the length of the panel and making thermal contact with the sheets via graphite foam (Pocofoam$^{\text{TM}}$) saddles. Multiple units were manufactured and assembled into radiator demonstration units (RDUs). After initial testing with panels embedded with three Ti/water HPs, a 2$^{\text{nd}}$ generation RDU was fabricated with sixteen Ti/water HPs per panel. This RDU was designed to reject at least 6 kW$_{\text{th}}$ using an inlet temperature of 400 K while radiatively rejecting to a 150 K liquid nitrogen shroud thermal sink used to simulate the space environment. Figure 7.14 shows a picture of the 2$^{\text{nd}}$ gen RDU prior to installation in VF-6 at GRC (left) and a thermograph of the RDU panel during testing (right). For the tests, heat was delivered to the RDU using a Ti-water fluid manifold with a flow rate of 0.25 kg/s. While the nitrogen shroud temperature was 150 K, the experimental data obtained were used to calculate the radiative heat transfer capability of the radiator assuming rejection to a 250 K thermal sink, which was the requirement for the FSP system (ref. [268]).

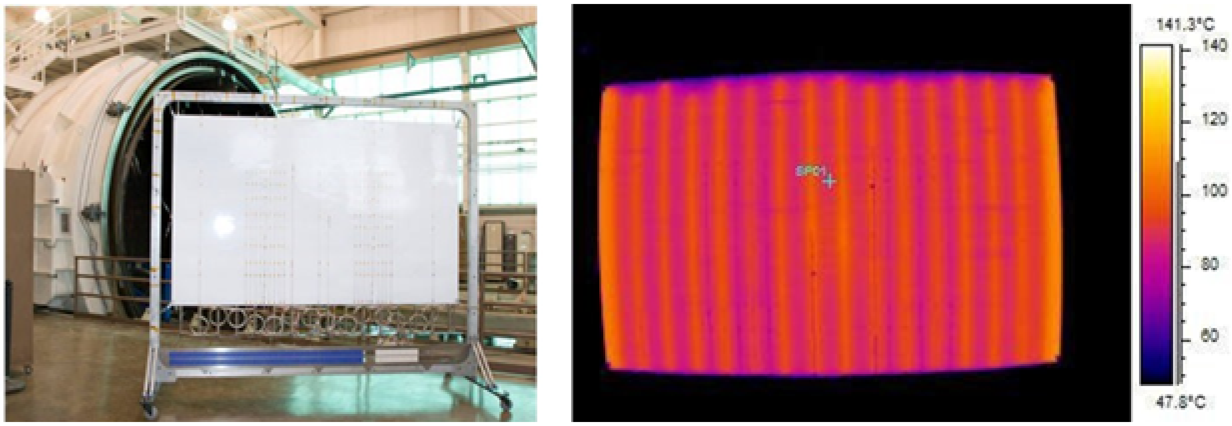
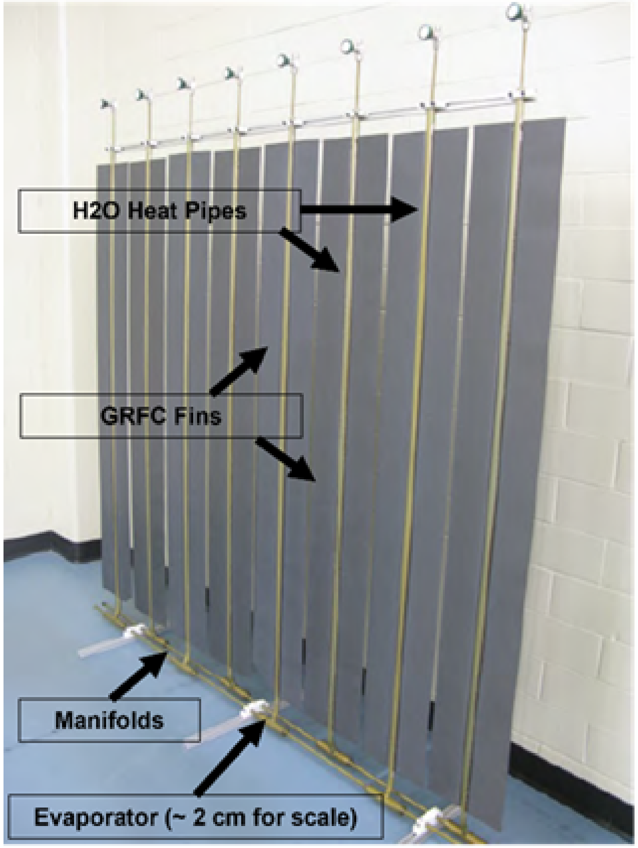
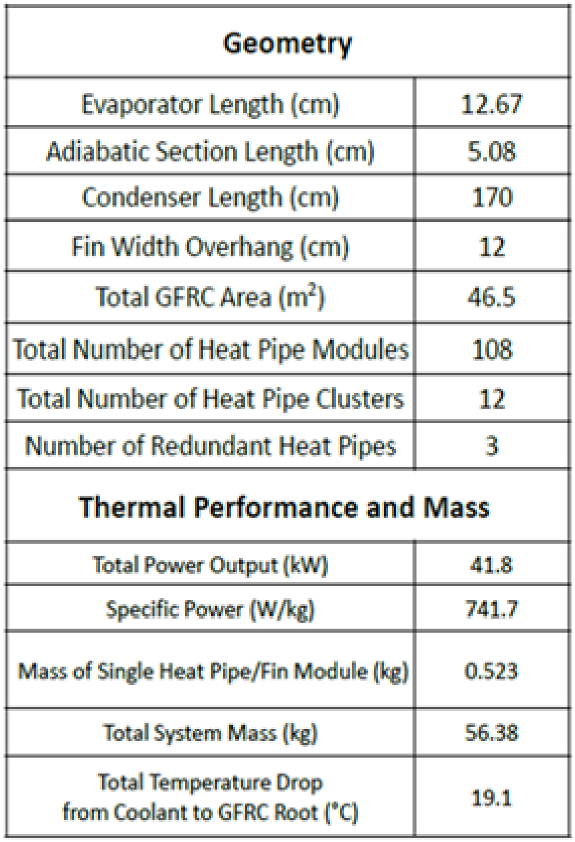


Figure 7.14: 2nd Gen RDU Panel Fabricated by Material Innovations Inc., with sixteen embedded titanium-water HPs (left), and a thermograph of the panel being tested with an inlet temperature of 400 K (right).

NASA's FSP project has recently examined low-cost radiators that might eliminate the complexity of the honeycomb sub-structure and the need for Pocofoam^{TM} saddles (ref. [262]). These fins are composed of a single graphite-reinforced fiber composite (GRFC) radiator sheet that is epoxy-bonded to the Ti/water HP. It was found that single HP fin structures could be grouped in clusters to yield larger radiator panels, with Figure 7.15 showing an assembly of this cluster-based panel assembly (left) possessing the nominal dimensions and thermal capabilities displayed in the right-hand table.





Geometry	
Evaporator Length (cm)	12.67
Adiabatic Section Length (cm)	5.08
Condenser Length (cm)	170
Fin Width Overhang (cm)	12
Total GFRC Area (m^2)	46.5
Total Number of Heat Pipe Modules	108
Total Number of Heat Pipe Clusters	12
Number of Redundant Heat Pipes	3
Thermal Performance and Mass	
Total Power Output (kW)	41.8
Specific Power (W/kg)	741.7
Mass of Single Heat Pipe/Fin Module (kg)	0.523
Total System Mass (kg)	56.38
Total Temperature Drop from Coolant to GFRC Root (°C)	19.1

Figure 7.15: Low-Cost, Cluster-Based Radiator Panel Assembly (ACT with Vanguard) for FSP.

The radiators developed for Project Prometheus and FSP are much smaller in scale and coolant flow rate than what would be expected for the high-power NEP application, but there is some overlap in their respective operating temperature ranges. Existing radiators have also demonstrated materials compatibility with working fluids and joining techniques and possess projected lifetimes sufficient to complete an NEP-powered human Mars mission.

The FSP program has established a HP test capability (shown in Figure 7.16) that was used to evaluate nine separate HP designs developed by different vendors. These HPs were operated at a hot-side temperature of 500 K over a cumulative total duration of two years with little observed change in performance (ref. [269]). This test capability and the experience base developed under the FSP project are directly relevant to the NEP application.

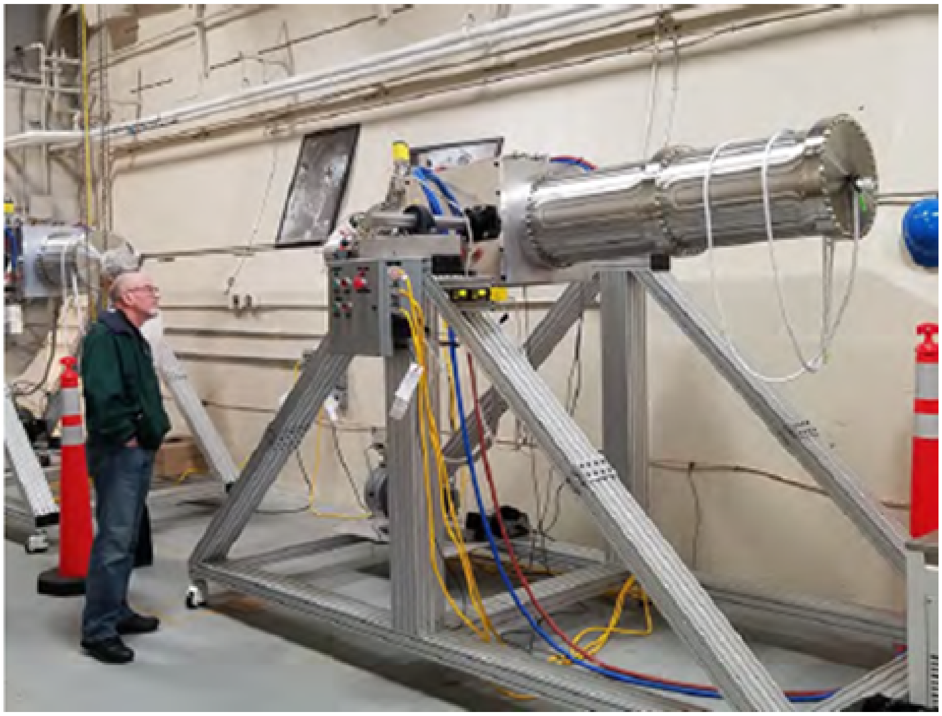


Figure 7.16: Heat Pipe Test Facility at GRC.

The outlet temperature from the PCS may exceed the maximum operating temperature ($T \geq 600$ K) of water HP technology leading to the consideration two additional solutions:

1. The use of a liquid metal mixer between the trunkline inlet and outlet used to moderate the trunkline temperature to remain within water HP operational limits; and
2. The addition of a second type of radiator/HP that is capable of higher temperature operation at the hottest side of the system.

The first option would be favored if it resulted in PHRS operation at or below the water HP temperature limit for all radiator panels. The second option is more complex (requiring two radiator/working fluid technologies) and may still require a mixing system to assure temperature compatibility at the interfaces. In either case, the mixing technology exists, and implementation is considered straightforward engineering that does not required further discussion here.

Alkali Metal Heat Pipes/Finned Radiators: For higher temperature applications, large-scale development efforts have been focused on the development of Na, K, and Li HPs coupled to finned radiators (refs. [263, 264, 265, 266, 267]). Successful HP research and development efforts have included the testing of Na HPs ($\sim$5 $\mathrm{kW_{th}}$ capacity) employing various wick materials. The targeted FSP applications for these HPs require coupling to Stirling power conversion systems with operation at hot-side temperatures over 900 K.

Relevant demonstrations of high-temperature (Na) HPs include:

1. A SAE 316L stainless steel pipes with a sintered porous nickel (Ni) wicks that was operated for over 115,000 hours at temperatures just below 1000 K (ref. [263]); and

2. An 87,000-hour demonstration of an Inconel 718-sleeve/stainless steel wick device at nearly 1000 K (ref. [263]).

In addition, mass reduction efforts led to the development of the high thermal conductivity carboncarbon (C-C_f) sodium HP with integral fins shown in Figure 7.17 (refs. [266, 267]).

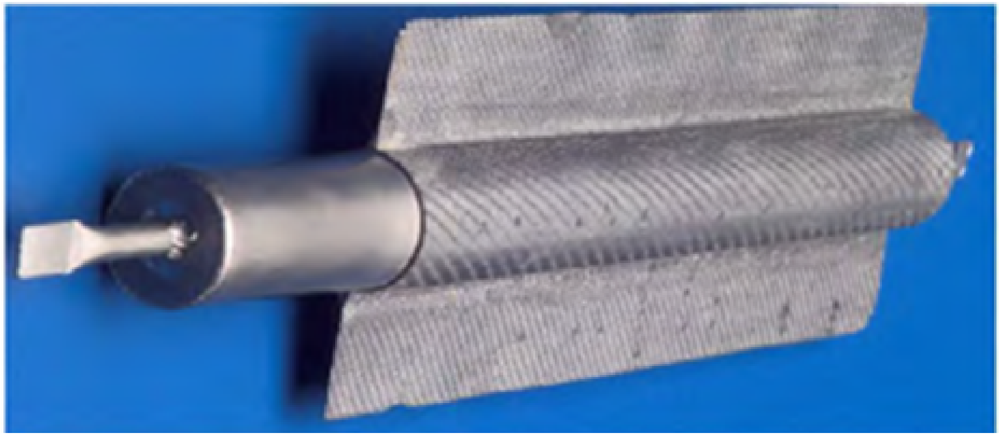


Figure 7.17: High Thermal Conductivity C-C Na HP with integral fins.

Similar to Ti/water HP technology, the work on alkali metal HPs to date provides an excellent foundation for the initiation of focused research and development of high temperature HPs for a MW_e-class NEP system, but extensive work will still be required for advancement to TRL 5.

Oscillating Heat Pipes (OHP): Heat spreading may become an issue as the panel scale increases. There are technologies other than the traditional wick-based HP design that might yield a more uniform heat distribution and may even allow for operation over a greater temperature range. Specific technologies such as OHPs (refs. [30, 270, 271, 272, 273]) and thermosyphons (refs. [262, 274]) were considered. The OHP technology using water-based fluids is considered to be the most likely alternative to conventional HP technology.

First developed by Akachi (ref. [270]), OHPs (also known as pulsating heat pipes) provide an alternative to conventional HPs. OHPs are wickless and employ a serpentine path of closed capillary channels partially filled with the working fluid. During operation, heat transfer is accomplished through the oscillation of liquid plugs and vapor bubbles, with the heat source partially vaporizing more of the liquid and the sink partially recondensing it. Significant experimental and modeling research on OHP operation has been performed over the past decade (see, for example, refs. [275, 276]). While early applications were mainly focused on relatively small-scale devices for the cooling of electronics, NASA is investing resources to explore the efficacy of OHP technology for larger-scale aeronautical applications (e.g., hypersonic vehicle leading edge cooling) and as radiators for both spacecraft and FSP. Figure 7.18 shows, from left to right, a simplified conceptual view of an OHP device, a 2 m^2 lightweight square aluminum breadboard panel, and an IR image of a 1.7 m^2 copper bent pipe OHP in operation using a proprietary working fluid.

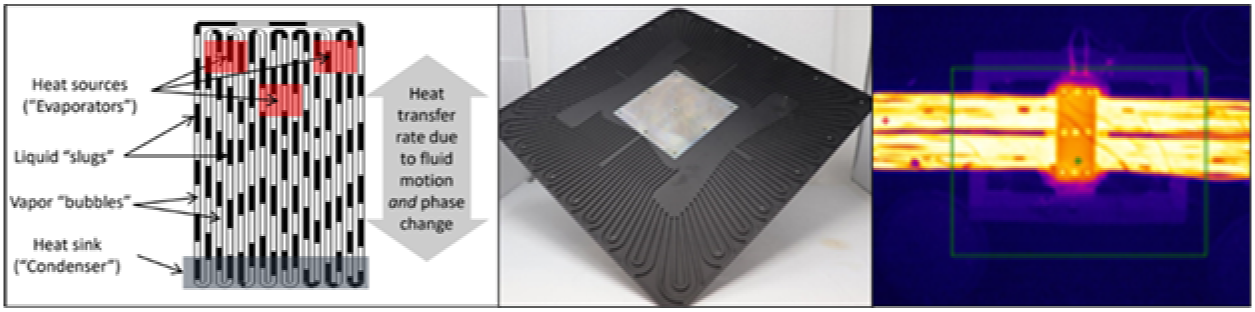


Figure 7.18: OHP Technology. The convection of alternating liquid plugs and vapor bubbles (left), a 2 m^2 aluminum spacecraft radiator panel (center), and an IR image of a 1.7 m^2 bent copper tube unit in operation (right). All images provided by ThermAvant.

The OHPs shown were developed under NASA SBIR funding (contracts 80NSSC19C0206 and 80NSSC21C0545). OHPs are attractive for their high heat spreading capabilities, their projected low areal densities, and their simplicity. To date, the majority of research and development on OHP radiators for space-based applications has focused on the use of aluminum with either water or proprietary working fluids. These systems are projected to possess a working temperature up to 75 K above the limit of conventional wicked water HP technology. Recent developments and demonstrations of panels with multiple fluidically-independent capillary channels capable of meeting DoD standards for reliability/failure (ref. [277]) have alleviated initial SME concerns about damage tolerance (e.g., catastrophic panel loss due to MMOD on single loop units). To date, however, most OHP development has focused on aluminum as the radiator panel material. A higher temperature material, such as titanium or carbon, may be needed for the high-power NEP application.

Surface Treatments: The spectral characteristics (IR emissivity, solar absorptivity, and IR absorptivity) of radiator panel surfaces must be considered in the context of system level optimization, and surface treatments are often used to increase panel emissivity. In general, surface treatments fall into two broad categories – surface texturing and coatings. While many surface treatments have been considered, there is no single "ideal" treatment that provides both high emittance ($\geq$0.9) and low solar and IR absorptance ($\leq$0.2) in the temperature range of interest. While the emissions of carbon-based radiator fin materials under consideration are temperature dependent, they fall in the range of 0.85–0.90. The use of high emissivity coatings to increase surface radiation is standard practice in the aerospace industry and extensive studies on engineering coatings have been performed for applications such as the Crew Exploration Vehicle (ref. [278]). The ISS radiators (shown in Figure 7.1), for example, are coated with a plasma sprayed Z93P white coating to increase surface emissivity while maintaining a low solar absorptivity (refs. [279, 280]). Z93 has demonstrated long-term durability in the space environment, and with an emissivity of $\sim$0.91 and solar absorptivity of $\sim$0.15, this paint is nearly ideal for many applications. There are multiple alternate white coatings tailored for specific applications (see, for example, ref. [281]). Unfortunately, while these paints exhibit excellent adhesion to bare aluminum, an inorganic primer is required for use with titanium or carbon-based surfaces and available primers are only stable to approximately 200 °C (473 K). Multiple versions of plasma-sprayed coatings have been evaluated by the Materials International Space Station Experiment (MISSE) project, specifically the

MISSE 6 and MISSE 7 experiments (ref. [282, 283]). One of these involved the evolution of a plasma sprayed coating designated PS–16. The PS-16 coating has excellent emissivity (∼0.93), a solar absorptance below 0.3 and was used on the Gravity Recovery and Interior Laboratory (GRAIL) carbon-carbon composite radiators (ref. [284]). However, the radiator temperatures on GRAIL were well below the high-power NEP temperature range of interest.

Carbon-carbon composite materials like the type used in conjunction with high temperature sodium HPs have been textured using atomic oxygen exposures to achieve emittances in the range of 0.9 (ref. [285]), and this serves as the target beginning of life (BOL) value for the SNP NEP application. Other surface modification methods for metals such as arc- and ion-discharge chamber texturing (refs. [286, 287]) have been explored with an emphasis on emissivity enhancement (all with essentially no discussion of absorptivity).

Requirements on the optical properties of the CTE-5 radiator surface will depend on the radiator surface material, the operating temperature range, and mission flight profile. Early SME assessments are planned to determine surface treatment requirements based on realistic potential advancements. SME inputs have indicated that the development of a high temperature primer for paint application is unlikely (ref. [288]) and that system-level alternatives that reduce surface treatment impacts should be explored. If, for example, a bi-wing radiator configuration is selected, with the spacecraft flown such that the panels are aligned edge-on to the sun, then an etched or sandblasted titanium array panel with high emissivity (>0.9) “black” coatings (e.g., Aremco 840-M - ref. [289]) sprayed onto the panels may be an appropriate option.

The need for high emissivity coatings for NEP is recognized and was the subject of a recent NASA’s SBIR solicitation (ref. [290]). If three-dimensional (e.g., oft-cited tri- and quad-wing/ cruciform) radiator systems are considered for an NEP system, then the panels cannot be exclusively oriented edge-on to the sun and treatments must additionally possess a low solar absorptivity. As an aside, such panel configurations place the wings in a partial line-of-sight with each other, which also reduces radiator effectiveness as some radiation emitted from one panel is reabsorbed by another. A clear path to an acceptable coating that can handle the operating temperatures of the radiators in a high-power NEP system and meet the added solar absorptivity requirement does not exist (and may not be physically possible). An appropriate coating may eventually be developed, but until that time the present TMP does not assume its availability and instead assumes a purely bi-wing configuration flown edge-on to the sun to eliminate the solar absorptivity issue.

Assembly/Deployment Considerations: A $\mathrm{MW_e}$-class NEP radiator assembly would be the largest structure ever developed for in-space use. The size of the PHRS required to radiatively reject enough heat for a multi-$\mathrm{MW_e}$ NEP system points to the need to develop the means to either deploy the system after launch and/or to assemble the system from piece-parts once they are launched into space. In-space assembly of structures, one of the areas of focus for ISAM, has been identified as a critical national space capability that could have large and far-reaching effects on the design and assembly of a large NEP vehicle (refs. [291, 292]). The ability to launch separate components and perform assembly and integration of systems in space offers potential to reduce the limitations imposed by the need to assemble complex hardware on the ground, package it to fit within a rocket fairing, survive the launch environment, and finally execute an often-complicated multi-step deployment (unfolding) in space. In an NEP system, all radiators require thermal contact with the trunkline working fluid, so in-space assembly methods must include detailed consideration of fluid interface integrity and a reliable method for post-assembly introduction of a working fluid into the system. This area of advancement is presently outside the ISAM project scope and must be addressed by SNP (working with ISAM to the greatest extent possible). With the growing market of launch vehicles and launch capabilities and the general reduction in launch costs, in-space assembly could enable an NEP system designed to execute a mission without the conventional constraint requiring the packaging of the entire radiator to squeeze it into a single payload fairing or include complex mechanisms for post-launch deployment. These fold-out deployment concepts require joints and fluid connections that have some compliance or flexibility, and deployable systems of this size are not within the present state-of-the-art.

In-space assembly would greatly facilitate the use of large bi-wing radiator structures that can be maintained in an orientation edge-on to the sun to reduce both radiator mass and sensitivity to solar heat flux. This is as opposed to a system that might be more readily packaged within a launch vehicle fairing, but that would likely be heavier and potentially less effective (as in the case of triand quad-wing designs). It is noted that panel packaging in a launch vehicle fairing and deployment in-space is the present state of the art, and many NEP mission and architecture studies have assumed a deployable panel design. Examples of these are shown in Figure 7.19 (ref. [30]). One could envision an option where folding, deployable panels may be used in conjunction with inspace assembly methods, with panels more fully deploying prior to or after the joining or welding operations that affix the panels to the overall structure and establish the high temperature connections between the radiator panels and the trunkline.

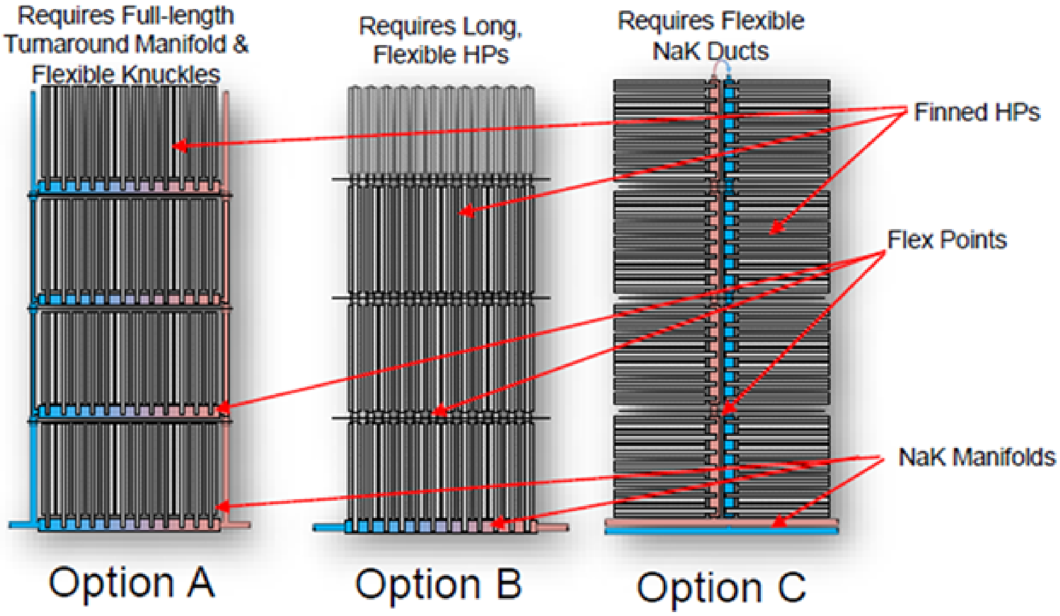


Figure 7.19: Radiator Panel Design Options. (Adapted from TIM presentation by Aerojet Rocketdyne. See ref. [30]).

Presently, there is not enough information to select technology specific fluid connectors for focused advancement work. The development plan presented in the remainder of this section, however, does carry the advancement of a flexible, high temperature connector, of a design to be determined at the initial PHRS workshop and to be refined through the work performed to advance PHRS technologies to TRL 4. The radiator-specific gaps in the current SOA and required advancements are described in Table 7.3.

Table 7.3: Major PRHS Radiator Technology Gaps and Advancement Requirements.

	Technology	**Gaps and Advancement Descriptions**
1	Working Fluids	Several options exist but given the temperature range of interest no single fluid may be the best option for the application. Less mature concepts like multi-fluid systems (where different fluids are used depending upon the temperature range) may be options but require significant work at the interfaces between each fluid. In addition to nominal operation, there may also be instances (startup, idle) where the temperatures are far from the nominal PHRS inlet and outlet temperatures. Final selection of the radiator working fluid(s) is required and must be reviewed and agreed to by SNP SMEs in the first NAR.
2	Heat Pipes	HPs (for radiators) have been demonstrated with both water and sodium, but not at the required power-levels and for the required durations. OHPs operate differently from wicking HPs and provide an option that uses water or other (proprietary) fluid mixtures to span a wider range of operating temperatures relative to conventional water HPs. Non-optimal operating conditions must be considered in the selection of the HP design.
3	Radiator Panels	Panel materials, design schemes, and bonding technologies exist but must be developed for NEP temperature ranges. Panels must be scaled in size over an order of magnitude larger than the present SOA to provide the required radiative capability (4+ $\mathrm{MW_{th}}$), meet the required areal mass densities for a low α system, and tolerate all environmental concerns (e.g., MMOD damage, operation after cold soak).
4	Fluid Connectors/Joints	Connector technology must be developed to provide the ability to assemble and/or deploy the system in space. The connections must be tailored to the NEP application, including, for example, high temperature operation, compatibility with the selected fluids (potentially including water, Na, and NaK), and leak-free operation over a lifetime greater than 25,000 hours.

7.2 PHRS Technology Advancement Plans

The SNP PHRS maturation goal is to develop and demonstrate an end-to-end PHRS subsystem (CTE-5) to TRL 5 in a four-year time frame. This will require advancing the SOA first to TRL 4/AD^2 3 in approximately two years. Table 7.4 shows a consolidated list of the major aspects of the PHRS to be addressed by SNP.

Table 7.4: CTE-5 Major Technology Gaps and Advancement Requirements. (the testing required to attain TRL 4 may be separable and could entail independent panel and pump tests (as recommended by SNP SMEs at the outset of the project). Integrated testing will be required to attain TRL 5.)

	Gap	**Advancement Descriptions**
1	Radiator Panels (including Connectors)	Development and demonstration of 50 kW$_{th}$-class radiator panels. Single panel BB-fidelity test with representative interfaces in relevant environment for 1,000 hours to attain TRL 4; BrB-fidelity testing of multiple/connected panels (2,500 hours) with pumped-loop thermal trunk line and return emulator to attain TRL 5. The radiator panel design must include a connector capable of remote mating with the trunkline emulator (actual remote mating demonstration not required for panel TRL advancement).
2	Liquid Metal Pump	Development and demonstration of an efficient liquid metal EM pump or mechanical pump capable of operation at the CTE-2/CTE-5 interface temperature at liquid metal flow rates. Demonstration of the transport of at least 1 MW$_{th}$ for a 1,000-hour using BB-fidelity hardware to attain TRL 4 and 3 MW$_{th}$ for 2,500-hour using BrB-fidelity hardware to attain TRL 5, with predictive modeling capability projecting 20,000+ hour life validated with results from TRL 4 and TRL 5 test sequences.

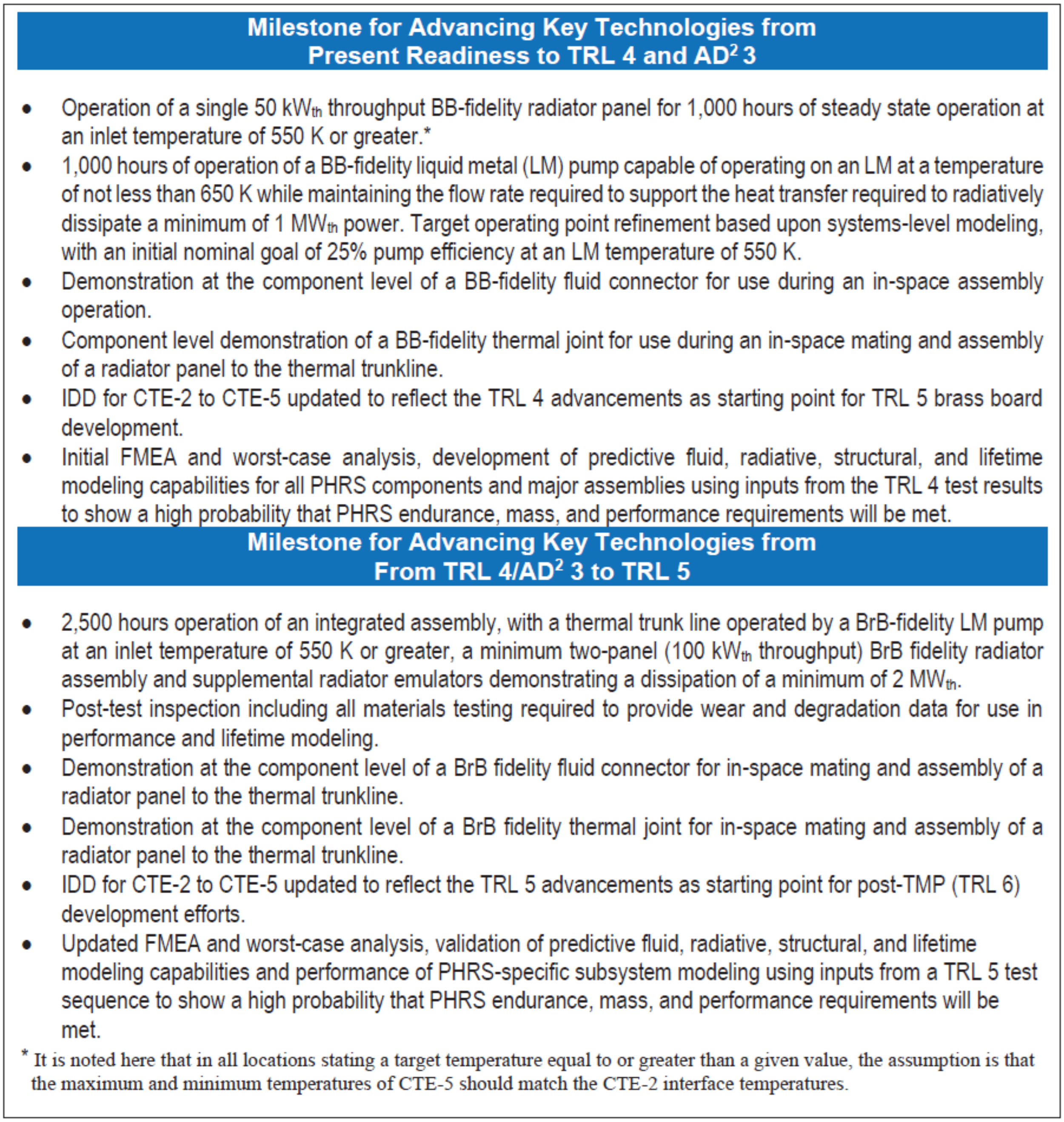
Table 7.4: CTE-5 Major Technology Gaps and Advancement Requirements. (the testing required to attain TRL 4 may be separable and could entail independent panel and pump tests (as recommended by SNP SMEs at the outset of the project). Integrated testing will be required to attain TRL 5.)

	Gap	**Advancement Descriptions**
3	Modeling & Simulation	Development of a predictive modeling capability demonstrating an understanding of the PHRS operational scaling and the controllable parameters, with the ability to project 20,000+ hours of life validated using results from TRL 4 and TRL 5 test sequences. Stepwise development of a modeling suite (thermal, mechanical, structural, environmental) to understand the CTE-5 subsystem for future NEP system design and development efforts. As part of the modeling and simulation effort, the development of a detailed FMEA is planned to ensure that the CTE-5 subsystem will meet all reliability requirements. For this, both internal PHRS failure modes and failure modes associated with CTE-to- CTE integration and operation (including the effects of transients and anomalies in other CTEs) will be evaluated and addressed.
4	Fluid Connectors	Development and demonstration of flight-like, high-temperature, liquid-metal-compatible trunk line-to-panel interconnectors designed for remote/robotic assembly. Testing of a quarter-scale unit for TRL 4 advancement and a full-scale unit for TRL 5.
5	CTE-2/CTE-5 Interface Emulator	Development of a thermal interface assembly to provide representative thermal input conditions to the trunkline assembly (including the liquid metal pump). Capability to support single panel operation (power throughput of 50 $\mathrm{kW_{th}}$) to attain TRL 4 followed by testing with a minimum of two panels plus additional panel emulators equivalent to roughly the thermal throughput needed for 1 $\mathrm{MW_e}$ power generation to attain TRL 5.
6	Liquid Metal Trunkline	Development of a laboratory-fidelity trunkline capable of supporting TRL 4 and TRL 5 test sequences for radiator panel and liquid metal pump maturation.
7	Controls/Sensors	Demonstration of controls (valves) and sensors sufficient to support planned radiator panel testing (transient and steady state).
8	Facilities	Development or upgrade of large-scale facilities and associated systems required for single panel testing (50 $\mathrm{kW_{th}}$) to attain TRL 4 and multi-panel testing to attain TRL 5. Moderate (10^{-4} torr) vacuum and spacerepresentative radiative viewing temperatures required.

Table 7.4: CTE-5 Major Technology Gaps and Advancement Requirements. (the testing required to attain TRL 4 may be separable and could entail independent panel and pump tests (as recommended by SNP SMEs at the outset of the project). Integrated testing will be required to attain TRL 5.)

	Gap	**Advancement Descriptions**
9	Assembly & Deployment Capabilities	Coordination with ISAM project to ensure synergy in the development and demonstration of technologies for PHRS assembly and deployment, including hardware and systems specific to an NEP system.

Specific goals to advance the TRL/AD^2 from the present SOA are shown in Figure 7.20. Note that "relevant conditions" refers to conditions that were determined or assumed in the system modeling employed to set the initial KPPs (as described in Table 7.1). Assuming the system is capable of supporting power generation of 1 MW$_e$ (through either a single MW$_e$ power generation block or two 500 kW$_e$ blocks), and that the power conversion efficiency is roughly 25%, then the relevant power throughput for the PHRS is approximately 3 MW$_{th}$.



Milestone for Advancing Key Technologies from Present Readiness to TRL 4 and AD^2 3

- Operation of a single 50 kW_{th} throughput BB-fidelity radiator panel for 1,000 hours of steady state operation at an inlet temperature of 550 K or greater.*
- 1,000 hours of operation of a BB-fidelity liquid metal (LM) pump capable of operating on an LM at a temperature of not less than 650 K while maintaining the flow rate required to support the heat transfer required to radiatively dissipate a minimum of 1 MW_{th} power. Target operating point refinement based upon systems-level modeling, with an initial nominal goal of 25% pump efficiency at an LM temperature of 550 K.
- Demonstration at the component level of a BB-fidelity fluid connector for use during an in-space assembly operation.
- Component level demonstration of a BB-fidelity thermal joint for use during an in-space mating and assembly of a radiator panel to the thermal trunkline.
- IDD for CTE-2 to CTE-5 updated to reflect the TRL 4 advancements as starting point for TRL 5 brass board development.
- Initial FMEA and worst-case analysis, development of predictive fluid, radiative, structural, and lifetime modeling capabilities for all PHRS components and major assemblies using inputs from the TRL 4 test results to show a high probability that PHRS endurance, mass, and performance requirements will be met.

Milestone for Advancing Key Technologies from From TRL 4/AD^2 3 to TRL 5

- 2,500 hours operation of an integrated assembly, with a thermal trunk line operated by a BrB-fidelity LM pump at an inlet temperature of 550 K or greater, a minimum two-panel (100 kW_{th} throughput) BrB fidelity radiator assembly and supplemental radiator emulators demonstrating a dissipation of a minimum of 2 MW_{th}.
- Post-test inspection including all materials testing required to provide wear and degradation data for use in performance and lifetime modeling.
- Demonstration at the component level of a BrB fidelity fluid connector for in-space mating and assembly of a radiator panel to the thermal trunkline.
- Demonstration at the component level of a BrB fidelity thermal joint for in-space mating and assembly of a radiator panel to the thermal trunkline.
- IDD for CTE-2 to CTE-5 updated to reflect the TRL 5 advancements as starting point for post-TMP (TRL 6) development efforts.
- Updated FMEA and worst-case analysis, validation of predictive fluid, radiative, structural, and lifetime modeling capabilities and performance of PHRS-specific subsystem modeling using inputs from a TRL 5 test sequence to show a high probability that PHRS endurance, mass, and performance requirements will be met.

* It is noted here that in all locations stating a target temperature equal to or greater than a given value, the assumption is that the maximum and minimum temperatures of CTE-5 should match the CTE-2 interface temperatures.

Figure 7.20: Key Milestones in the CTE-5 PHRS Advancement Strategy.

To meet these TRL advancement goals, milestone-driven schedules have been developed for:

1. The advancement of each major assembly (MA) at the BB and BrB fidelity levels,
2. Integrated demonstrations of BB- (TRL 4) and BrB-fidelity (TRL 5) hardware at 1,000 and 2,500 hours, respectively, with the concurrent advancement of modeling capabilities to demonstrate understanding of the important and controlling physical phenomena

in the system, to aid in the prediction system preference and lifetime capability for a full-duration mission, and

3. The assembly or upgrading of facilities and infrastructure required to support all required testing.

The detailed milestones for advancement to TRL 4, the timing of these milestones (starting at Q1/Y1 measured from ATP), and the significance with respect to advancement progress are shown in Table 7.5. The schedule for advancement to TRL 4/AD^2 3 (with a NAR to confirm advancement) is shown in Figure 7.21 The detailed milestones for advancement to TRL 5 is given in Table 7.6. The schedule for advancement to TRL 5 (with NAR) is shown in Figure 7.22. Table 7.7 shows the detailed milestones with timeframes and short descriptions of the significance of each facility development effort with respect to the overall development effort. A top-level schedule for the development of facilities required for the advancement of CTE-5 hardware from SOA through TRL 5 is provided in Figure 7.21. It is noted that there are many existing government and commercial vacuum facilities that have the size, pumping capacity, and cold shrouds required for testing the PHRS through TRL 5. Consequently, no major facility construction should be required for the planned CTE-5 advancements. These existing facilities include, for example, VF-6 at GRC, which has been used for similar testing in programs like FSP and the Mark 1 chamber at the Arnold Engineering Development Center. Streamlining development through the use of one common facility will be a high project priority. The potential for integrated testing with other CTEs (as opposed to the use of emulators for the interfaces) will also be explored.

Table 7.5: Key PHRS TRL 4/AD^2 3 Demonstration Milestones.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
SME Technical Planning Workshops	CTE5-1.1	Q1/Y1	Preliminary recommendations developed for 1) working fluids, 2) panel technology & design options, 3) liquid metal pump technology, 4) trunkline configuration, and 5) facility requirements and provided to SNP management for baselining. Input and output interface emulator design requirements established. Preliminary risks and hazards lists generated.
Preliminary Radiator Panel Development Options Review	CTE5-1.2	Q2/Y1	SME review with recommendations for specific primary panel design option with alternate option(s) for risk reduction (if deemed necessary by SNP).
Preliminary Liquid Metal Pump Design Review	CTE5-1.3	Q2/Y1	SME review with recommendations for a specific liquid metal pump design option with alternate option(s) for risk reduction (if deemed necessary by SNP).

Table 7.5: Key PHRS TRL 4/AD^2 3 Demonstration Milestones.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Heat Exchanger and Trunkline Emulator Review	CTE5-1.4	Q2/Y1	Design review for laboratory heat exchanger and trunkline hardware to be employed in BB radiator panel and liquid metal pump testing (separately or together as recommended by SNP SMEs at Milestone 1 workshop).
Initial IDD Draft Complete	CTE5-1.5	Q3/Y1	SME developed interface description document developed.
Alternate High-Emissivity Coatings Review/Selections	CTE5-1.6	Q3/Y1	SME review of high-emissivity coating candidates with recommendation to SNP for accelerated environmental testing (including facility selection) – SNP authority to proceed with testing.
Liquid Metal Pump Design Review	CTE5-1.7	Q3/Y1	SNP review of primary liquid metal pump option BB design - authority to proceed with acquisitions.
Radiator Panel Design Review	CTE5-1.8	Q3/Y1	SNP review of primary radiator panel option BB design - authority to proceed with acquisition. Radiator panel design to include connectors compatible with robotic mating to trunkline.
Preliminary Liquid Metal Fluid Connector Design Review	CTE5-1.9	Q4/Y1	SNP/ISAM SME review of “most likely” candidate designs for robotic assembly connectors for trunkline-to-panel liquid metal connections. Recommendation of primary and backup options for development. Authority to proceed with primary design.
Heat exchanger and Trunkline Emulator Delivery	CTE5-1.10	Q4/Y1	All emulator hardware delivered to BB test facility with SME inspection.
Interim M&S and FMEA Review	CTE5-1.11	Q4/Y1	SME review of progress on both M&S and FMEA progress heading into the BB test sequence – SME recommendations to assure test plans include required measurements.
Heat exchanger and Trunkline Installation	CTE5-1.12	Q1/Y2	All support hardware for BB panel and liquid metal pump testing installed and operational for panel and pump testing (separately or together as recommended by SNP SMEs at Milestone 1 workshop).
Radiator Panel Delivery & Installation	CTE5-1.13	Q1/Y2	50 kW$_{\mathrm{th}}$ BB radiator panel delivered, inspected by SME’s, installed in BB test facility.

Table 7.5: Key PHRS TRL 4/AD^2 3 Demonstration Milestones.

Major Technology Milestones to TRL 4	**#**	**Timeframe (End Date)**	**Significance**
Liquid Metal Pump Delivery & Installation	CTE5-1.14	Q2/Y2	Delivery of up to 25 kW$_e$ BB liquid metal pump, inspected by SME's and installed in BB test facility.
BB-fidelity hardware Test Readiness Reviews	CTE5-1.15	Q2/Y2	SNP TRR for approval to proceed with initiation of radiator panel and liquid metal pump BB testing (together or separate (TBD)).
Interim BB Test Progress Reviews	CTE5-1.16	Q2/Y2	SNP review of BB testing after 100 hours of operation – authority to proceed to full 1,000-hour test (with modifications in test setup and procedures if required).
Alternate High-Emissivity Coating Review	CTE5-1.17	Q2/Y2	Review of coating development after roughly 1 year of testing – SME recommendation of coating selection for TRL 5 testing.
Liquid Metal Fluid Connector Design Review	CTE5-1.18	Q2/Y2	Collaborative SNP/ISAM review of liquid metal fluid connection hardware development effort – authority to continue with development and testing.
M&S Progress Review	CTE5-1.19	Q2/Y2	SME review of M&S progress incorporating BB test data.
BB Hardware Testing Complete	CTE5-1.20	Q3/Y2	BB testing of radiator panel and liquid metal pump complete – results compiled and delivered to SNP for NAR.
Final M&S and FMEA Reviews	CTE5-1.21	Q4/Y2	SNP review of M&S and FMEA documents prior to delivery for NAR.
TRL 4 NAR	CTE5-1.22	Q4/Y2	NAR to confirm CTE-5 technology advancement to TRL 4.
Final IDD, FMEA, and Risk & Hazards Lists Complete	CTE5-1.23	Q4/Y2	Final TRL 4 IDD, revised as necessary for BrB emulator development. Revisions to risk and hazards lists complete and delivered to SNP.

Table 7.6: Key PHRS TRL 5 Demonstration Milestones.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
BrB Design Review Workshops (Radiator, Liquid Metal Pump, Emulators)	CTE5-2.1	Q1/Y2	SME review of hardware development plans for 100 kW_{th} (minimum) BrB-class, multi-panel radiator and up to 50 kW_e liquid metal pump demonstrators. Review provides assurance that lessons-learned from BB hardware fabrication & testing are incorporated. Also provides definition of TRL 5 emulator and test facility requirements. Authority to proceed with long-lead component acquisition. Risk and hazards lists reviewed and revised as necessary.
Interim BrB 100 kW_e Panel Assembly/Integration Review	CTE5-2.2	Q2/Y2	BrB design review for fabrication of at least two (2) 50 kW_{th}-class panels for invacuum testing including interconnection design and facility requirements.
Interim Liquid Metal Pump Review	CTE5-2.3	Q2/Y2	BrB design review for fabrication of a (minimum) 1 MW_{th}-class (minimum) trunkline including the liquid metal pump. Review to include SME approval of facility requirements and the designs for interconnections emulators, and other related equipment.
Initial TRL 5 M&S/FMEA Planning Session	CTE5-2.4	Q2/Y2	Review of M&S progress for TRL 4 test sequences and recommendation of deltarequirements to support advancement to TRL 5.
BrB Radiator Panel and Liquid Metal Pump Designs Complete	CTE5-2.5	Q4/Y2	BrB hardware designs complete, SME review with recommendation to SNP – authority to proceed to procurement and fabrication.
Liquid Metal Fluid Connector Progress Review	CTE5-2.6	Q4/Y2	Collaborative SNP/ISAM review of liquid metal fluid connector testing progress – recommendations for continued testing and/or design revision).
TRL 5 Emulator & Trunkline Designs Complete	CTE5-2.7	Q4/Y2	Lessons learned from BB testing incorporated in TRL 5 design – authority to proceed with TRL 5 hardware procurement and fabrication.
BrB Hardware Delivery & Inspection (Panels & Liquid Metal Pump)	CTE5-2.8	Q2/Y3	All BrB hardware delivered and assembled into the TRL 5 test configuration (e.g., inter-panel connections completed, all emulators connected).
Liquid Metal Fluid Connector Design Finalized	CTE5-2.9	Q3/Y3	SNP/ISAM-approved design complete – authority to proceed to liquid metal fluid connector fabrication (if different than existing design).

Table 7.6: Key PHRS TRL 5 Demonstration Milestones.

Major Technology Milestones to TRL 5	**#**	**Timeframe (End Date)**	**Significance**
Emulator & Trunkline Hardware Installed	CTE5-2.10	Q2/Y3	All emulator and trunkline hardware installed and operational for BrB testing.
100-Hour Shakedown TRR	CTE5-2.11	Q2/Y3	Review to assure 100-hour BrB hardware shakedown test(s) readiness at 100 kW_{th}.
Interim M&S/FMEA Review	CTE5-2.12	Q4/Y3	SME review of 1) current FMEA (updated based on BB-fidelity hardware testing and 100-hour BrB shakedown tests at 100 kW_{th}) and 2) all M&S results and readiness for modeling (with requirements for validation) of MW_e-class system.
100-Hour Shakedown Test Review	CTE5-2.13	Q3/Y3	SNP review of BrB multi-panel test at the 100-hour mark with authority to continue to 2,500-hour goal (with modifications if required).
Final TRL 5 M&S/FMEA Report Drafts Complete	CTE5-2.14	Q3/Y4	FMEA and M&S updated with incorporation of data from endurance testing – report to SNP in preparation for NAR.
Liquid Metal Fluid Connector Testing Complete	CTE5-2.15	Q3/Y4	Testing of liquid metal fluid connector complete – recommendations by SNP/ISAM team for advancement to implementation (TRL 6) phase.
BrB Test Complete/SNP Review	CTE5-2.16	Q3/Y4	2,500-hr BrB test complete – Panels and liquid metal pump disassembled, inspected, and results documented. Lessons-learned captured for next phase (prototype development).
TRL 5 NAR	CTE5-2.17	Q4/Y4	NAR to advance multi-panel radiator assembly and liquid metal pump technology to TRL 5.
Final IDD, FMEA, and Risk & Hazards Lists Complete	CTE5-2.18	Q4/Y4	IDD revised as necessary based upon BrB development and delivered to SNP. Revisions to risk and hazards lists complete and delivered to SNP.

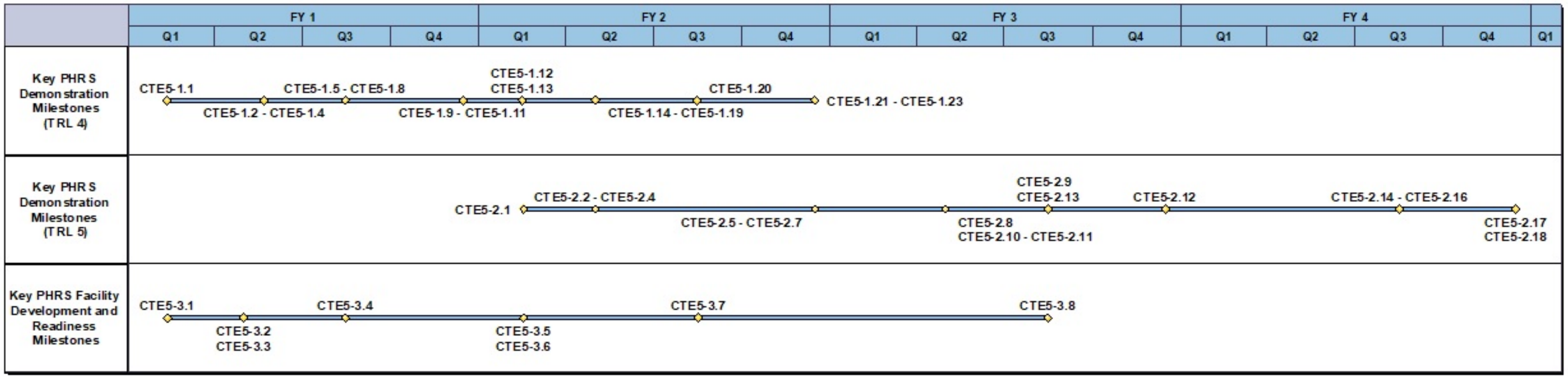


Figure 7.21: CTE 5 Advancement Schedule

Table 7.7: Key PHRS Facility Development and Readiness Milestones.

Facilities Developments	**#**	**Timeframe (End Date)**	**Significance**
SME Facilities Planning Workshop	CTE5-3.1	Q1/Y1	Facility Requirements Workshop and Options Review.
Requirements for TRL 4 Testing Facilities Complete	CTE5-3.2	Q2/Y1	Requirements for TRL 4 Testing Facilities Complete/Facilities Selection.
TRL 5 Facilities Options Characterized	CTE5-3.3	Q2/Y1	Preliminary options for TRL 5 facilities evaluated.
TRL 4 Facility Development Progress Review	CTE5-3.4	Q3/Y1	SME status review for TRL 4 facilities.
TRL 4 Facilities Readiness Review	CTE5-3.5	Q1/Y2	TRL 4 facility achieves initial operating condition.
TRL 5 Facilities Selection Review	CTE5-3.6	Q1/Y2	Final TRL 5 facility selected.
TRL 5 Facility Development Progress Review	CTE5-3.7	Q3/Y2	SME status review for TRL 5 facility.
TRL 5 Facilities Readiness Review	CTE5-3.8	Q3/Y3	TRL facility achieves initial operating condition.

This schedule provides for advancement of the key technologies on the MA level to TRL 4/AD^2 3 over the first two years. This includes component advancement and testing as required and burnin operations on larger assembly tests prior to a long-duration test. The schedules show all the advancements occurring independently in separate, dedicated facilities, but there may be substantial overlap in facility usage given the possibility of performing integrated PHRS testing early in the development program. Advancement of individual MA technologies to TRL 5 (including early procurements and planned facility upgrades) should start at the earliest practical time. The anticipated timeframe for advancement from TRL 4 to TRL 5 is three years with tasks beginning during the second year of the TRL 4 advancement schedule and running to the end of the fourth year of the plan.

Delivery of BB (TRL 4/AD^2 3) and BrB (TRL 5) fidelity hardware for integrated testing is planned for the middle of years 2 and 3, respectively. Facility initial operating condition (IOC) dates and major TRRs for associated duration testing occur in this same timeframe. It should be noted that while the schedules shown are ambitious, the test sequences are planned with significant funded margin. For example, the 2,500-hour integrated test to meet TRL 5 acceptance criteria is scheduled over a roughly 10-month period, which gives roughly 7,200 hours to complete the planned 2,500- hour test.

7.3 CTE-5 Technology Advancement Risks

The SNP project has performed a preliminary development risk assessment of the heat rejection system with the support of non-advocate SMEs. This assessment is the start of a formal FMEA, the results of which will be documented as part of the overall PHRS technology development effort.

A list of the technology maturation challenges and risks associated with the PHRS, based on SME consensus, is as follows:

- Radiator coating optical property lifetime
- Liquid metal pump performance/reliability
- Heat exchanger performance/reliability (CTE-5 side)
- Freeze/thaw of working fluid in thermal trunkline
- Materials interactions between working fluid and piping
- Fluid connections in thermal trunkline compatible with deployment and/or in-space assembly
- Inlet radiator temperature control
- Heat-spreading in radiator panels
- Thermal coupling between radiator panel heat conduction lines and the thermal trunkline
- Development of in-space assembly and deployment strategies and technologies in conjunction with the ISAM community.

Table 7.8 lists the top five preliminary technical risks identified by SNP SMEs. Risks are rated using NASA's standard risk scale for consequence and likelihood from Goddard Procedural Requirements (GPR) 7120.4D, Risk Management Reporting. The risk ranking is summarized in Figure 7.22. It is noted that the availability of long-life surface treatments that have both high emissivity and low solar absorptivity is not listed among these top five risks because this is considered a binary mission driver. If, in fact, no applicable surface treatment is found, this will drive the NEP system design to a planar bi-wing PHRS configuration that must be flown edge-on to the sun for a significant fraction of the mission.

Table 7.8: ‘Top 5’ PHRS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

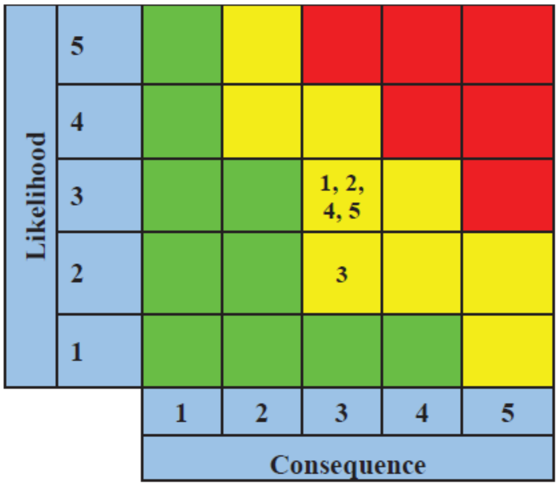
Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PHRS-1	PHRS Thermal Trunkline Working Fluid	Projected operating temperature range and reliability considerations dictate the use of liquid metals (alkali eutectics), which have potential handling and materials compatibility issues.	T	3	3	9	1. Materials testing to demonstrate long-term compatibility of working fluid with trunkline hardware, with NAR evaluations. 2. Investigation of alternative liquid-metals (such as galliumbased eutectic alloys). 3. Schedule reserve for iterative testing with technology infusion/upgrades (if required) implemented prior to each test sequence.
PHRS-2	Liquid Metal Pumps	Pump reliability, efficiency, lifetime, and transient behavior (startup and shutdown)	T	3	3	9	1. Early assessment of pump requirements. 2. Parallel development of electromagnetic and mechanical pump designs. 3. Testing at temperatures, pressures, and flow rates for 2,500 hours (conditions commensurate with the conduction of a minimum of 1 MW_{th} power).

Table 7.8: 'Top 5' PHRS system risks and mitigation strategies. (L-likelihood, C-consequence, T-total)

Risk #	**Risk Title**	**Risk Statement**	**Risk Type**	**Risk Assessment**			**Mitigation Strategies**
				L	C	T	
PHRS-3	Heat Pipes	Working fluid capable of operation over the required temperature range. Material compatibility of HP material with working fluid. Adequate heat spreading throughout radiator panel.	T	2	3	6	1. Development and testing of HPs at operating temperatures with several working fluids to determine combinations that are compatible and that perform at the required operating temperatures. 2. Development and testing of several candidate heat-panel designs and thermal spreading strategies.
PHRS-4	Liquid Metal Fluid Connections	Size of radiator array dictates deployment and/or in-space assembly; fluid connectors compatible with liquid metals required for assembly of the thermal trunkline.	T	3	3	9	1. Development and testing of a liquid-metal-compatible fluid connector. 2. Testing of the thermal mating of radiator panels to a thermal trunkline emulator.
PHRS-5	Thermal interface between thermal trunkline and radiator panels	Size of radiator array and maturation of technology dictates deployment and/or in-space assembly; Radiator panels need close thermal coupling to thermal trunkline	T	3	3	9	1. Testing of radiator panel deployment in ground facility. 2. Test mating of radiator panels with a thermal trunkline in ground facility using ISAM techniques.

7.4 PHRS Summary

SNP has developed the maturation plan detailed here to advance the technologies (thermal trunkline, radiator panels, deployment and ISAM techniques) required for a MW$_e$-class Pri-



Likelihood	5	🟩	🟨	🟥	🟥	🟥
	4	🟩	🟨	🟨	🟥	🟥
	3	🟩	🟩	🟨 1, 2, 4, 5	🟨	🟥
	2	🟩	🟩	🟨 3	🟨	🟨
	1	🟩	🟩	🟩	🟩	🟨
		1	2	3	4	5
		Consequence				

Figure 7.22: PHRS ‘Top 5’ Risk Ranking Likelihood and Consequence Span.

mary Heat Rejection System (PHRS) through TRL 4 to TRL 5 on both the major assembly level and as a fully integrated system. The milestone-driven schedule will, if fully funded, produce a PHRS subsystem (CTE-5) that has attained TRL 5 and is ready for integration in a larger NEP system design. The plan depends upon hardware demonstration efforts supported by the development of predictive modeling and simulation capabilities, with non-advocate review for all key milestones to independently verify that TRL advancement has occurred. While the plan was developed for performance in a four-year time frame, the development tasks are, to a large extent, separable. So long as the SE&I tasks are performed to keep all tasks and interfaces between CTEs and major assemblies in sync with each other, meaningful incremental progress can be achieved through specific targeted technology maturation investments pursued at the discretion of SNP as funds become available.

Chapter 8

Conclusions

Over the course of fiscal years (FY) 2022 and 2023, the Space Nuclear Propulsion (SNP) project authored a Technology Maturation Plan (TMP) to guide development of the key technologies needed for a megawatt-class Nuclear Electric Propulsion (NEP) vehicle suitable for human missions to Mars in the late 2030s or early 2040s. This plan was created in direct response to two major independent reviews of the state of nuclear propulsion for spaceflight: one conducted by the National Academies of Science, Engineering, and Medicine (NASEM) and the other conducted by the NASA Engineering and Safety Center (NESC). Both the National Academies and NESC reports concluded that the Technology Readiness Levels (TRLs) of NEP subsystems are too low to support the development of a flight project or even a serious preliminary vehicle design without first undertaking significant technology maturation to reduce design risk and uncertainty.

The present TMP is based on a comprehensive review of the state-of-the-art for NEP that began in FY 2021 and continued into FY 2022. From December 2020 through April 2021, several Technical Interchange Meetings (TIMs) were held with numerous government and industry Subject Matter Experts (SMEs) in attendance. The purposes of these TIMs were to aid in the assessment of the state of development of NEP technologies, identify specific, high-confidence, viable NEP system design options, and develop an understanding of the tasks required to mature critical technologies. TIMs were held on the following topics:

- Nuclear Reactor Design
- Power Conversion System
- Power Generation, Management, and Distribution
- Electric Propulsion
- Thermal Management
- In-Space Assembly

SNP personnel also met individually with many SMEs over the subsequent year to further clarify and better assess the state of NEP technologies. Those deliberations informed the formulation and writing of this TMP.

The NEP system is roughly divided into five subsystems, or Critical Technology Elements (CTE):

- CTE-1: Reactor and Coolant Subsystem (RXS)
- CTE-2: Power Conversion Subsystem (PCS)
- CTE-3: Power Management and Distribution (PMAD) Subsystem
- CTE-4: Electric Propulsion Subsystem (EPS)
- CTE-5: Primary Heat Rejection Subsystem (PHRS)

which operate in concert to realize an NEP propulsion system. Together with a chemical propulsion stage for high-thrust maneuvers, they constitute an NEP-Chem propulsion system of the type presently under consideration for human missions to Mars. During the formulation and writing of this TMP, SMEs developed a set of preliminary KPPs for each CTE based on performing these types of missions. Coupled system and mission modeling was used by the SNP team to set the value of overall system KPPs and the underlying subsystem KPPs that represent the developmental goals being targeted within this TMP. These values may change during the course of TMP execution as contemporaneous test data are used to refine system models and remove uncertainty from the overall system and mission models.

This TMP presents a plan, with detailed milestones and schedules, for incremental advancement of key technologies in all five CTEs, achieving advancement first to TRL 4 and then to TRL 5. Once completed, the performance, mass, and lifetime of an NEP system should be understood to the point where high confidence vehicle design and mission modeling could be undertaken in support of the development of a human mission. Based on the findings of the National Academies and NESC reviews, the primary purpose of this development effort is to build and test hardware at relevant operating conditions (power levels, temperatures, etc.), demonstrating the performance required for an NEP vehicle and providing test data that will permit informed decisions regarding further development. These data will also be used to support predictive modeling and simulation efforts and constrain performance assumptions to realistic and achievable values. The goals of the TMP are purposefully difficult to ensure significant technology advancement will have occurred at the conclusion of the effort.

The maturation plans for each CTE were written to be modular, using emulated interfaces at the CTE boundaries to permit development of any CTE independent of the others. The project will maintain control of these interfaces to ensure that the individual CTEs meet overall system requirements. Depending on schedules and available facilities, integrated testing of two or more CTEs may be attempted if the project judges this to be advantageous, but such testing is not necessary to complete the overall plan. The plan envisions a four-year development schedule from project start, if the effort is fully funded and implemented. Because of the separable nature of the plan, funding at a lower level would still permit progress, albeit at a slower pace. Based on lessons learned from past programs, the TMP stipulates that non-advocate reviews be conducted at all key decision points to ensure and verify that technology maturation has occurred.

The nominal technologies selected in this TMP for each CTE are summarized in Table 8.1. The choices and operational values are initial selections and will be refined during the course of TMP execution.

Table 8.1: Highest-Confidence Options as Identified for each NEP CTE

CTE-1: Reactor and Coolant Subsystem (RXS)	
Fuel	UN or UO_2, with clad pellet fuel form
Moderator	YH_x and BeO, or BeO
Reactor Heat Transfer	Direct Gas Cooled with He-Xe coolant or Li Heat Pipe Cooled
CTE-2: Power Conversion Subsystem (PCS)	
Closed Brayton cycle	Recuperated (likely)
Working Fluid	Helium-Xenon (He-Xe) mixture
Inlet Temperature	1200 K (threshold) / 1400 K (target)
Power Level per Unit	500 kW_e – 1 MW_e
Overall Vehicle Power Level	2-4 MW_e
CTE-3: Power Management and Distribution (PMAD) Subsystem	
AC Power Transmission	Voltage: 1 kV Frequency: 2 kHz
CTE-4: Electric Propulsion Subsystem (EPS)	
Hall Thrusters	Propellant: Xenon Power per Thruster: 100-250 kW_e
MPD Thrusters	Propellant: Lithium Power per Thruster: 500 kW_e – 1 MW_e
CTE-5: Primary Heat Rejection Subsystem (PHRS)	
Pumped-Loop Thermal Trunkline	Working Fluid: Liquid Metal
Finned C–C Radiator Panels w/Embedded Heat Pipes	Working Fluid: Water and/or Alkali Metal

In some instances, there was an overwhelming consensus by SMEs that permitted initial technology down-selections, and these were implemented in advance of the drafting of the TMP. Examples include:

CTE-1: Pumped liquid-metal cooled reactors were deemed too difficult to develop in the required time frame based on the difficulties encountered in previous development programs.

CTE-2: At the required power levels, closed Brayton cycle converters were the clear consensus choice for power conversion. While He-Xe was the leading candidate for the working fluid, supercritical CO_2 (sCO_2) was also considered. However, based on early system modeling studies and investigations regarding corrosion in sCO_2 systems at high operating temperatures, it was concluded with high confidence that this option should be excluded from consideration. In addition to the difficult issues regarding chemistry and corrosion, it was found that, at the operating temperature of interest to minimize overall system mass, sCO_2-based systems did not offer any clear mass or performance advantages over systems utilizing the much more benign He-Xe working fluid.

CTE-4: A variety of thruster technologies were evaluated, including Hall thrusters, MPD thrusters, gridded ion thrusters, and VASIMR. All but Hall and MPD were excluded as having too low a system TRL and/or too high of an AD^2 at MW_e power levels.

Across several CTEs, it is not possible to presently select a single development path, given the high AD^2 for the various technology options. In these cases, at least two options are carried for further development until such time as one option emerges as the clear choice for further maturation. In these cases, decision points are included in the schedule at key milestones, permitting down-selects between parallel development paths when one technology option reaches a level of maturity that lowers the risk and uncertainty relative to further development.

This TMP reflects certain technology choices made by SNP, specifically choices that have been deemed as the most likely to result in successful near-term technology maturation to the point where those subsystems can support a future NEP system design. This is not to say that an offeror cannot propose technologies not selected within this TMP. However, to merit consideration, it must be shown that those alternatives provide a viable path to meeting the required KPPs and can be matured during the time frame of interest through an offeror-developed technology maturation plan. These offeror-developed plans would be required to meet the same level of detail and rigor as found in this TMP for the selected technology options, and such plans would be subject to review by the by the SNP project and a non-advocate review or a source evaluation panel prior to any potential selection.

The system modeling effort undertaken over the last two years has been used to generate system and subsystem-level KPPs and to inform the writing of this TMP. This effort will continue in parallel with the hardware development effort, with test results fed back into the computational effort to reduce modeling uncertainties, refine the KPPs, and provide further guidance to the project. Overall, the combination of hardware development and system models is necessary to enable informed technology selections required to realize operational NEP systems.

Appendix A

Acronyms and Nomenclature List

Term	**Meaning**
α	specific mass
α_{ps}	power supply specific mass
λ	latent heat of vaporization
η	thruster efficieny
kΩ	kiloohm
μF	microfarad
σ	surface tension
ρ	density
Ω	ohms
A	ampere
AC	alternating current
AD^2	advancement degree of difficulty
AEHF	Advanced Extremely High Frequency
AEPS	Advanced Electric Propulsion System
AGR	Advanced Gas Reactor
AHP	analytic hierarchy process
Al	aluminum
ALIP	annular linear induction pump
ANSI	American National Standards Institute
APU	auxiliary power unit
AR	Aerojet Rocketdyne
ARDP	Advanced Reactor Demonstration Program
ATF	accident tolerant fuel
ATP	authority to proceed
B	magnetic field
Ba	barium
BaO	barium oxide
BB	breadboard
Be	beryllium

Term	Meaning
Be_2C	beryllium carbide
BeO	beryllium oxide
BESS	battery energy storage systems
Bi	bismuth
BN	boron nitride
BrB	brassboard
BRU	Brayton Rotating Unit
C	carbon or carbide
C_f	carbon fiber
cc	cubic centimeter
CABLES	Connecting Aviation By Lighter Electrical Systems
CBC	closed Brayton cycle
Chem	chemical propulsion
CIT	compressor inlet temperature
cm	centimeter
cm^2	square centimeter
CONOPS	concept of operations
COTS	commercial off-the-shelf
Cs	cesium
CSAU	code scalability, applicability and uncertainty
CTE	critical technology element
DBTT	ductile to brittle transition temperature
DC	direct current
D&C	design and construction
DDU	direct-drive unit
DoD	Department of Defense (also Department of War [DoW])
DOE	Department of Energy
dpa	displacements per atom
DSU	discharge supply units
EA	electronic aircraft program
EATCS	external active thermal control system
EBR	Experimental Breeder Reactor
EDU	engineering demonstration unit
EIS	environmental impact statement
EM	electromagnetic
EPDM	Electric Propulsion Demonstration Module
EP	electric propulsion
EPS	Electric Propulsion Subsystem
ESEX	Electric Propulsion Space Experiment
F	fluoride
FA	fuel assembly
FE	fuel element
Fe-Si	silicon steel

Term	**Meaning**
FLiBe	lithium beryllium fluoride molten salt
FMEA	failure modes and effects analysis
FS	full-scale
FSP	fission surface power
FY	fiscal year
Ga	gallium
GRAIL	Gravity Recovery and Interior Laboratory
GRC	Glenn Research Center (formerly Lewis Research Center)
GPR	Goddard Procedural Requirement
H	hydrogen
HALEU	high-assay, low-enrichment uranium
He	helium
HERMeS	Hall Effect Rocket with Magnetic Shielding
HEU	highly enriched uranium
Hg	mercury
HP	heat pipe
HPCMTF	High-Power Condensable Metal Test Facility
HPR	heat pipe reactor
hr	hour
HTGR	High-Temperature Gas Reactor
Hz	hertz
I&C	instrumentation and control
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
IOC	initial operating condition
I_{sp}	specific impulse
ISAM	in-space servicing, assembly, and manufacturing
ISS	International Space Station
ISTP	In-Space Transportation Program
j	current density
JANUS	Joint AdvaNced PropUlsion InStitute
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory
K	Kelvin
K	potassium
kA	kiloamperes
keV	kiloelectron-volts
kg	kilogram
khours	kilohours
kHz	kilohertz
klb_f	kilo-pounds force

Term	Meaning
kN	kilonewton
kPa	kilopascal
KPP	key performance parameter
krad	kilo-radiation absorbed dose
krpm	kilo-rotations per minute
KRUSTY	Kilopower Reactor Using Stirling TechnologY
kV	kilovolt
$\mathrm{kW_e}$	kilowatt-electric
$\mathrm{LaH_6}$	lanthanum hexaboride
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
$\mathrm{LH_2}$	liquid hydrogen
Li	lithium
$^{6}\mathrm{Li}$	lithium-6 isotope
$^{7}\mathrm{Li}$	lithium-7 isotope
LM	liquid metal
LMR	liquid-metal-cooled reactor
LOx	liquid oxygen
LV	launch vehicle
LWR	light water reactor
MA	major assembly
MAI	Moscow Aviation Institute
MARVEL	Microreactor Application Research, Validation, and EvaLuation
MLI	multilayer insulation
MMOD	micrometeoroid and orbital debris
Mo	molybdenum
MoW	molybdenum-tungsten alloy
MPa	megapascal
MPD	magnetoplasmadynamic
M&S	modeling and simulation
MSFC	Marshall Space Flight Center
MT	metric ton, 1000 kg
MTAS	Mars Transportation Assessment Study
MVR	model validation review
MW	megawatt
$\mathrm{MW_e}$	megawatt-electric
$\mathrm{MW_{th}}$	megawatt-thermal
n	neutron
N	Newton
N	nitrogen
Na	sodium
NaK	sodium-potassium

Term	**Meaning**
NAR	non-advocate review
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NDDT	National Direct-Drive Testbed
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEAT	NASA Electric Aircraft Test Facility
NEP	nuclear electric propulsion
NEP-SIM	NEP system integration model
NEPA	National Environmental Policy Act
NESC	NASA Engineering and Safety Center
NextSTEP	Next Space Technologies for Exploration Partnerships
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NSSK	north-south station keeping
NSTAR	NASA Solar Technology Application Readiness
NTP	nuclear thermal propulsion
O	oxygen or oxide
ODS	oxide dispersion-strengthened
OECD	Organisation for Economic Co-operation and Development
OHP	oscillating heat pipe
OSU	Ohio State University
Pb	lead
PCIT	power conversion inlet temperature
PCS	Power Conversion Subsystem
PDR	preliminary design review
PHRS	Primary Heat Rejection Subsystem
PIE	post irradiation examination
PIRT	phenomena identification and ranking table
PL	parasitic load
PMAD	Power Management and Distribution Subsystem
PCU	power conditioning unit
PPE	Power and Propulsion Element
PPI	Plasma Processes, Inc.
PPU	power processing unit
Q	quarter
RAB	refractory alloy Brayton
Rad	radiation absorbed dose
RDU	radiator demonstration unit
RXS	Reactor and Coolant Subsystem
s	seconds

Term	**Meaning**
S/C	spacecraft
SAB	superalloy Brayton
sCO_2	supercritical carbon dioxide
SEE	space environment effects
SEI	Space Exploration Initiative
SEP	solar electric propulsion
Si	silicon
SiC	silicon carbide
S&MA	Safety and Mission Assurance
SMART	Small Missions for Advanced Research in Technology
SME	subject matter expert
SNAP	Space Nuclear Auxiliary Power
SNAPSHOT	SNAP Orbital Test
SNP	Space Nuclear Propulsion
SO_2	sulfur dioxide
SOA	state of the art
SOI	sphere of influence
SP-100	Space reactor Prototype-100
SpaceX	Space Exploration Technologies
SPT	stationary plasma thruster
SS	subscale
STEx	Space Technology Experimentation
STMD	Space Technology Mission Directorate
SWIFT	Stoichiometry With Internally Fluctuating Temperature
T	transformer
T_{boil}	boiling temperature of a substance
T_{melt}	melting temperature of a substance
TAL	thruster with anode layer
TAP	technology assessment process
TBD	to be determined
TCR	test completion review
TDU	technology demonstration unit
TEM	thermoelectric-electromagnetic
Ti	titanium
TIM	technology interchange meeting
TMP	technology maturation plan
TPU	turbine power unit
TRISO	tri-structural isotropic
TRL	technology readiness level
TRR	test readiness review
QMU	quantification of margins and uncertainties
U	uranium
UZrH	uranium zirconium hydride

Term	**Meaning**
^{235}U	uranium-235 isotope
U-Mo	uranium-molybdenum alloy
UO_2	uranium oxide
US	United States
V	volt
VDC	volts-direct current
W	tungsten
W_e	watts-electric
WBS	work breakdown structure
WBG	wide band gap
Xe	xenon
Y	yttrium
YH_x	yttrium hydride
Zr	zirconium
ZrC	zirconium carbide
ZrH_x	zirconium hydride

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