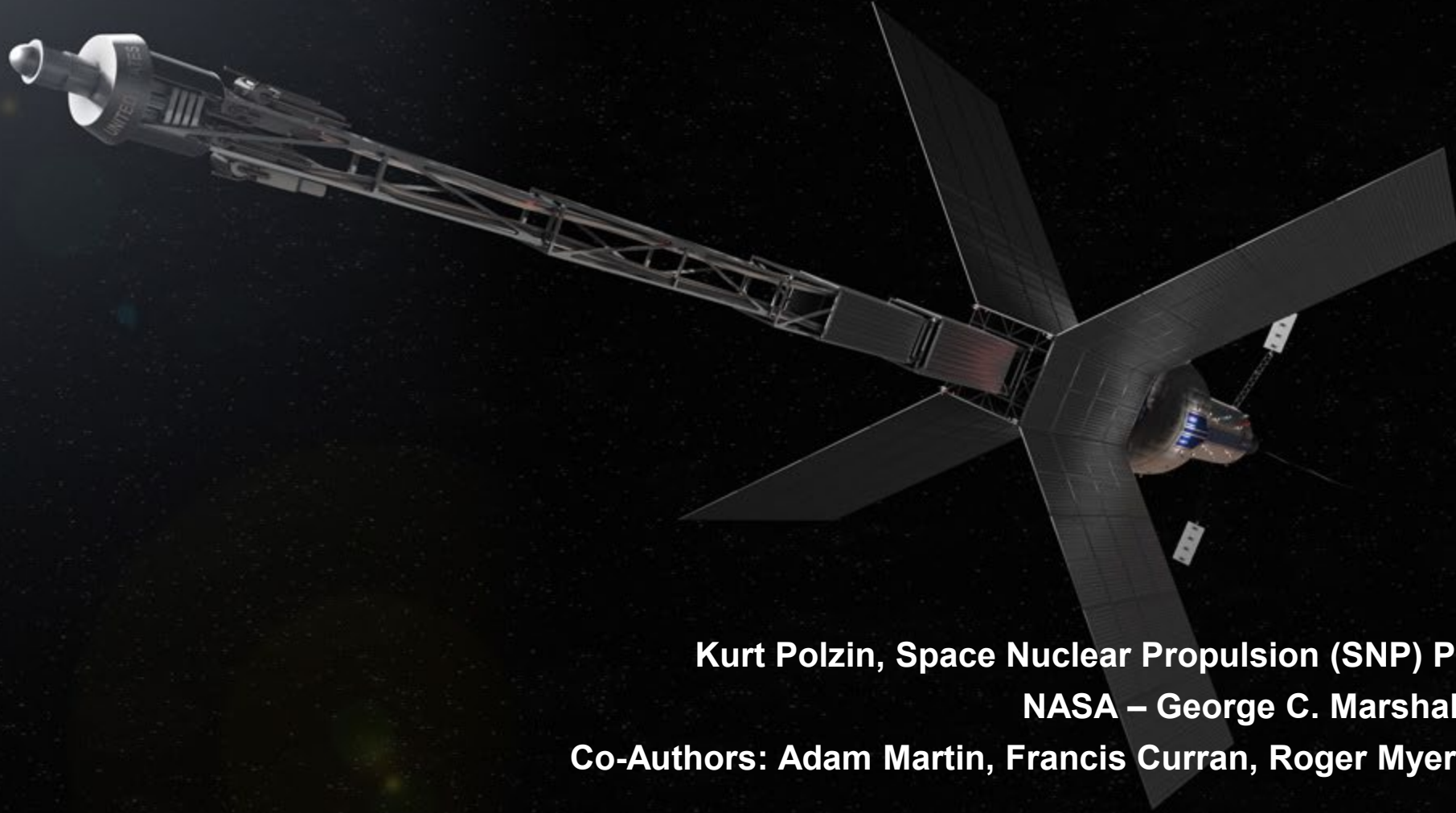


Strategy for Developing Technologies for Megawatt-class Nuclear Electric Propulsion Systems



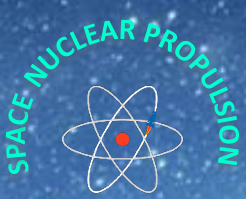
Kurt Polzin, Space Nuclear Propulsion (SNP) Project Chief Engineer

NASA – George C. Marshall Space Flight Center

Co-Authors: Adam Martin, Francis Curran, Roger Myers, Mitchell Rodriguez

2022 International Electric Propulsion Conference, Boston, MA

20-23 June 2022



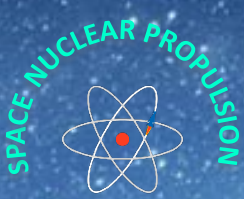
Past and Recent Efforts

Multiple NASA investments over past six decades

- SNAP (1960s)
- SEI in parallel with SP-100 (100-kW class, 1990s)
- JIMO/Prometheus (100-kW class, 2000s)

Several recent architecture studies for human-rated Mars missions (late 2030s opposition-class opportunities)

- MTAS (GRC)
- SNP project (AMA)
- Aerojet Rocketdyne



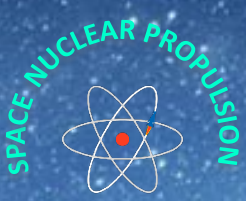
Motivation

SNP project charged w/formulating a strategy to develop required technologies for a high-power (multi-megawatt) NEP system for human-scale missions

Two recent, independent reviews found that the readiness for all major NEP subsystems required for a human-rated Mars mission are low

NASA Engineering and Safety Center (NESC) (2020)

- “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”

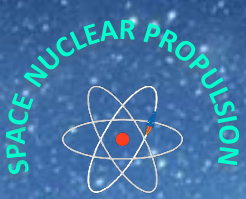


Motivation



National Academies of Science, Engineering, and Medicine (2021)

- “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)



SNP NEP Technology Maturation Strategy



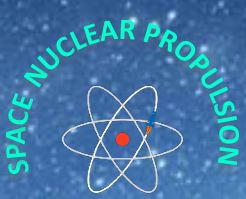
Responsive to the NESC and National Academies reviews

Realize TRL advancement through milestone-based hardware development and testing supported by modeling and simulation activities.

- Work at the sizes and scales necessary to bring all key NEP technologies to readiness levels where they can be credibly considered for a range of human Mars missions
- Modeling and simulation to demonstrate understanding of important and controlling physical phenomena and to aid in the prediction of lifetime capability for a full-duration mission

NEP technology maturation plan (TMP) not based upon a specific architecture / vehicle

- Many mission studies exist and 'close' for certain cases.. Give a feel for the mission NEP needs/requirements
 - Somewhere between 1-10 MW_e
 - Propulsion option selection & mission opportunity dependent
 - Large uncertainties due to commensurate uncertainties in mass/performance **at relevant scales**

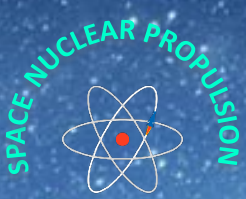


SNP NEP Technology Maturation Strategy



Maturation Efforts

- Work at sizes and scales relevant to the human Mars mission
- Based on recent mission studies, mission power level is between 1-10 MW_e
 - Project employs a 1 MW_e building block approach (calling this the 'relevant' scale)
 - Large step increase from current SOA flight or laboratory systems demonstrating any endurance
 - Building blocks large enough for credible, straightforward scaling into the 1-10 MW_e range by
 - Additional scaling to further increase system power capability or
 - Employing additional power generation and processing units in parallel



SNP NEP Technology Assessment

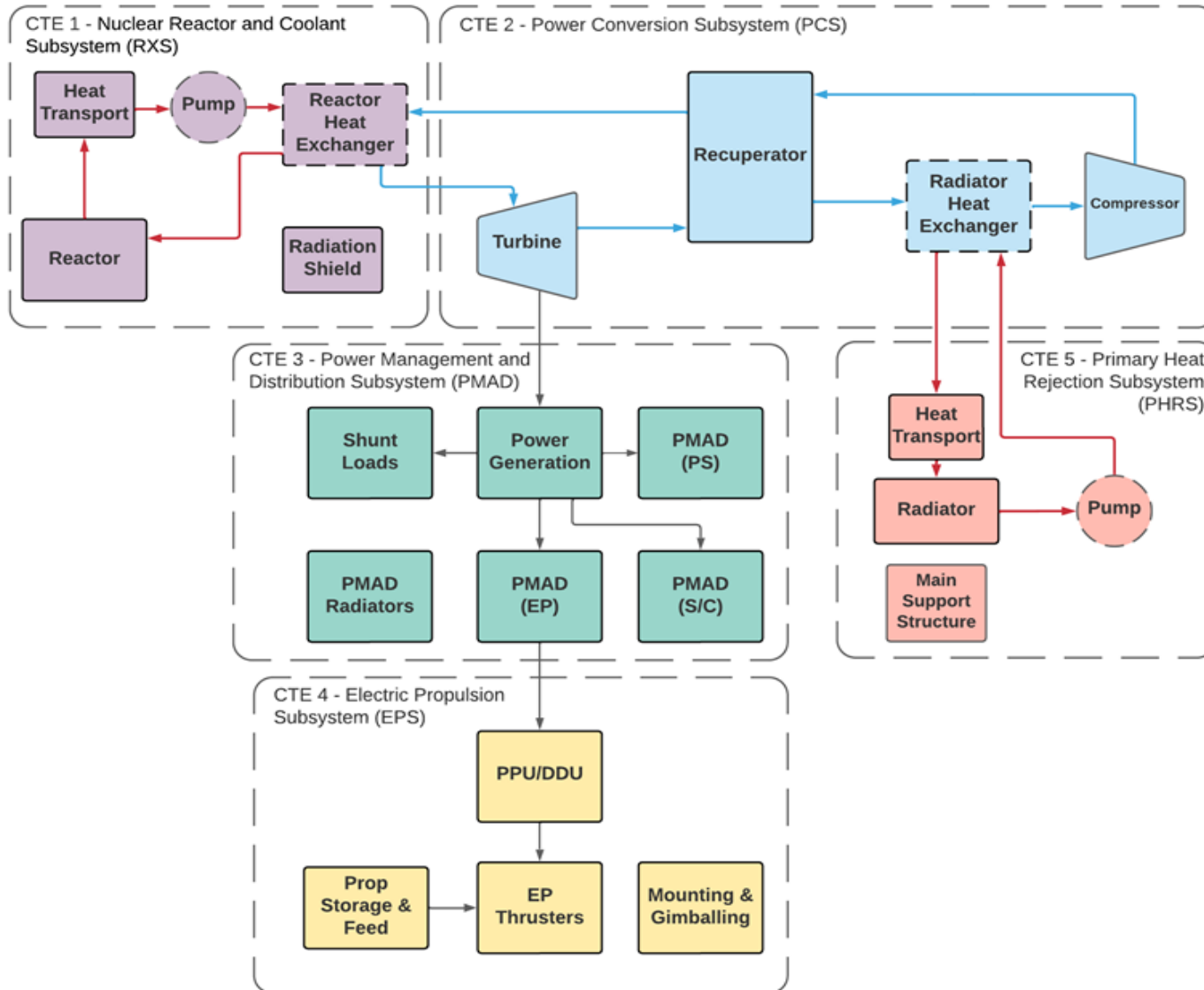


Detailed assessment over past two years

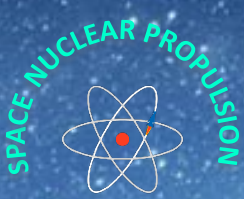
- Literature deep dives
- Several subsystem-focused Technical Interchange Meetings (Dec 2020 – Apr 2021)
- Large number of individual discussion with institutions, partners, and subject matter experts
- Investigated many available technologies, including those developed for applications outside of NEP (e.g., electric aircraft propulsion, gas turbine technologies for aircraft and power generation applications)
- Assess 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.
 - Won't discuss the options here (not yet baselined), but will discuss the tasks/milestones that will show technology demonstration

NEP Major Subsystems

- Critical Technology Elements (CTEs) -

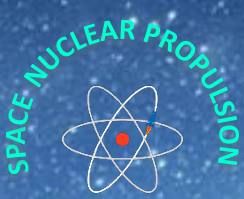


- Depending on design choices not all items shown in the figure will be needed
- Technology selections & optimization should be performed on the system level
- Use TRL (static description of status) and AD² (effort required to move from one TRL to the next) to quantify maturation
 - Goal is to increase TRL and decrease AD²



Major System and Key Subsystem KPPs

Parameter	KPP value
Power system α (kg/kW _e) [consists of CTEs 1, 2, 3, and 5]	20 (threshold), 13 (target)
Total electric propulsion thrust (N)	80-100
Electric propulsion efficiency and I_{sp} (s)	Efficiency and I_{sp} required to close mission – dependent on electric propulsion system choice
Mission duration (hours)	25,000
CTE 1 power output (MW _{th})	8-10
CTE 1 outlet/CTE 2 power conversion inlet temp (K)	1200 (threshold), 1400 (target)
CTE 2 power output (MW _e)	2-4
CTE 4 total thruster operating time (hours)	13,000-17,000 (EP system choice dependent)
CTE 2 outlet/CTE 5 inlet temp (K)	625-750
CTE 5 outlet/CTE 2 compressor inlet temp (K)	350-500



NEP Maturation Plan Major Milestones

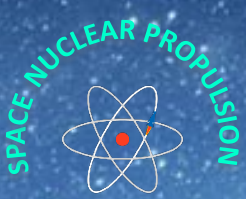


Maturation from present value to TRL 4/AD² 3, and then to TRL 5/AD² 2

- Focus is on the critical and long-lead developments
- Hardware-focused with accompanying modeling and simulation activities for each CTE
- Straightforward engineering / extensions of existing state-of-the art are not necessarily part of the plan

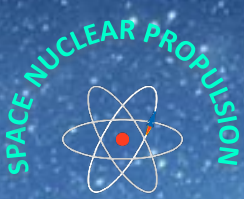
Not discussed in detail in this paper

- Test facilities needs
 - Many tests contemplated are challenging and will either require significant upgrades to existing facilities or the commissioning of new facilities
 - Capability to adequately simulate on-orbit environment may be a key discriminator for the technology selection process
- Modeling and simulation activities – of the overall integrated system
- Identification and development of the required instrumentation and control systems



Non-Nuclear NEP Maturation Major Milestones

- Example of general scope (CTEs 2-5) – expect some tailoring between CTEs and for different possible options within a CTE
 - Testing at specified hardware fidelity – provides evidence of operability at scale / data on system performance, mass, long-duration operation
 - Predictive modeling and sim capabilities using the test data for anchoring/validation
 - Outputs used to refine expectations on performance and system mass for future design and mission architecture studies (hardware testing at scale to reduce input uncertainty)
 - Predictions of lifetime and life-limiting failure mechanisms supporting FMEA
- Required hardware fidelity increases / milestones become more challenging to advance to higher TRL, including operation at 1 MW_e for 2,500 hours (or roughly 10% of the overall mission duration) for TRL 5.
- Non-advocate review of results to confirm achievement of milestones



Electric Propulsion Subsystem (CTE 4) Example

For advancement from the present status to TRL 4/AD² 3

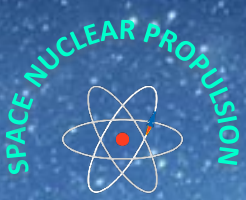
- Successful operation for 1000 hours of sub-scale breadboard-level fidelity thruster pod (with the number of thrusters and operational power level per thruster selected to support model validation) using power processing unit (PPU) emulators.
- Successful operation of an integrated single full-scale engine and PPU (both at breadboard-level fidelity) for a minimum of 1000 hours.
- Demonstration of predictive thermal, plume, and thruster/PPU interaction modeling capabilities, validated with data from the TRL 4 advancement effort.
- Delivery of a detailed preliminary failure modes and effects analysis (FMEA) showing no insurmountable issues that will prevent achieving program goals.

For advancement from TRL 4/AD² 3 to TRL 5/AD² 2

- Successful operation for 2500 hours of an integrated sub-scale thruster pod consisting of breadboard-fidelity thrusters and PPUs operating at the full scale that would be needed for a 1 MW_e capability (with the quantity of thruster/PPU elements in the pod set to ensure the capture of all effects associated with multi-thruster operation).
- Successful plume test of a pod of breadboard-fidelity thrusters operating in a facility of a size that is capable of quantifying plume effects.
- Demonstration of predictive thermal, plume, and thruster/PPU model capabilities validated with data from the TRL 5 advancement effort and used to extrapolate full-power pod-level performance, lifetime, and plume interaction impacts.
- Delivery of a final FMEA showing no insurmountable issues that will prevent achieving program goals.

Conclusions

- SNP project has formulated a methodical tech maturation strategy
 - Hardware-focused at relevant scales/conditions with accompanying modeling and simulation
 - Responsive to the NESC and National Academies conclusions on current NEP readiness
 - Incorporates inputs gathered through a detailed assessment of options
 - Focuses on 1 MW_e building blocks as the basis for TRL advancement
 - Plan is still under review / not yet baselined, but expect draft release for community comment during early FY Q4
- Acknowledgements: DV Rao, K Palomares, M. Duchek
- This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project



Questions

