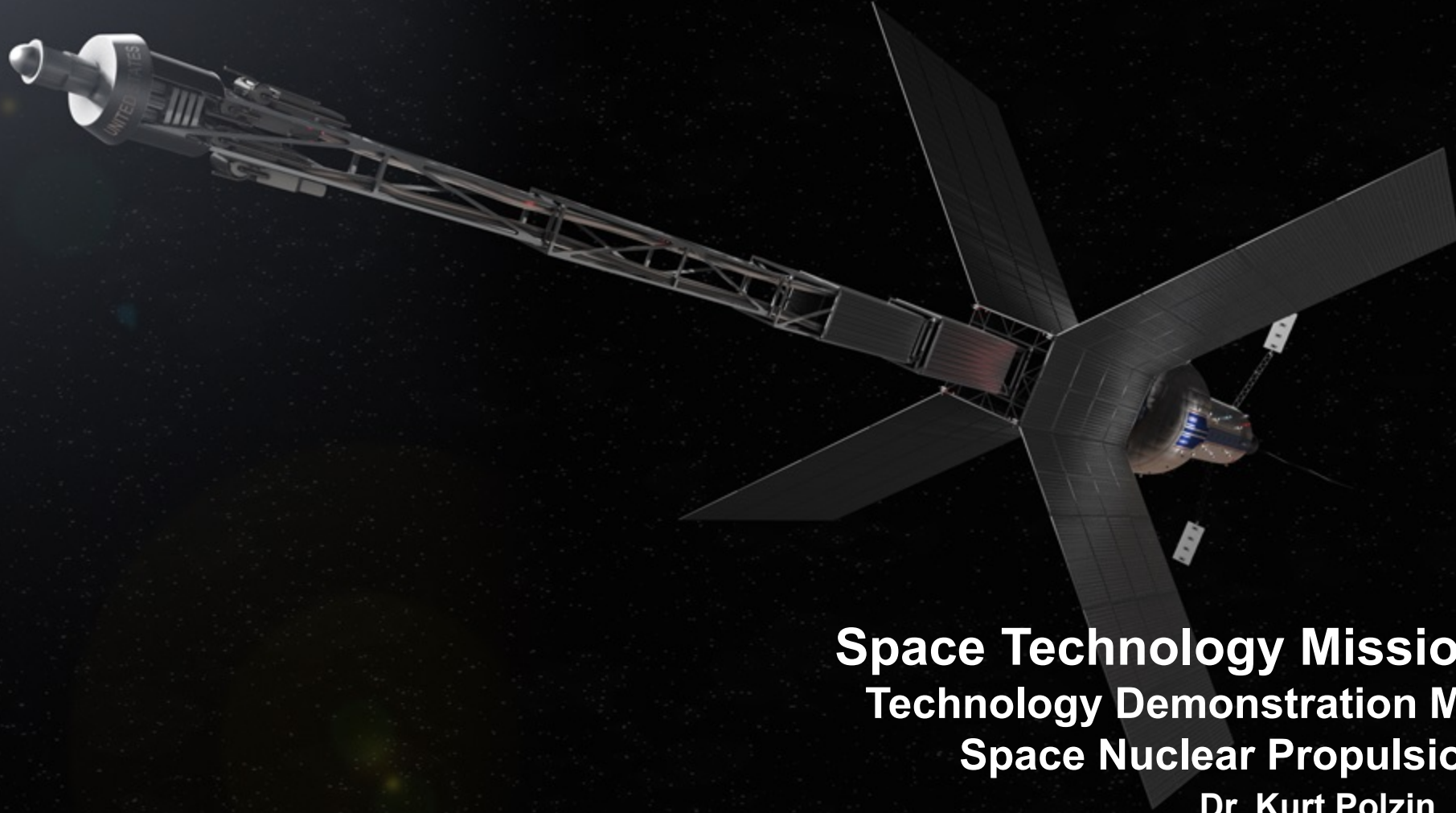


Technology Development for In-Space Nuclear Electric Propulsion

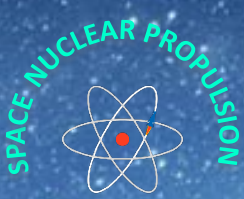


**Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion (SNP) Project**

Dr. Kurt Polzin, SNP Chief Engineer

NASA – George C. Marshall Space Flight Center

8 October 2021



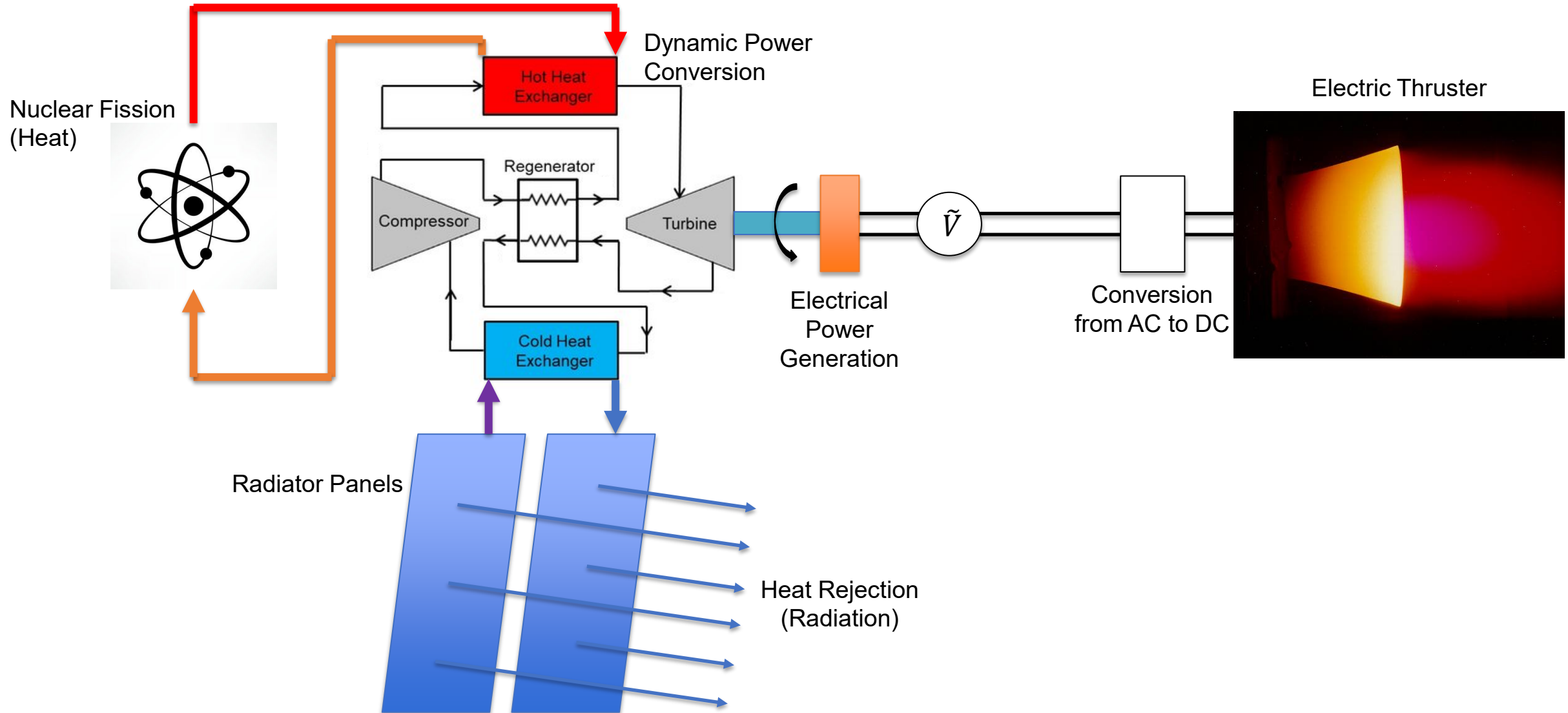
NASA's Space Nuclear Propulsion Project



- The MSFC Space Nuclear Propulsion (SNP) project has the responsibility for managing nuclear fission-related propulsion systems (nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP)) for NASA Space Technology Mission Directorate (STMD)
- The SNP project spent the last year identifying specific, high-confidence, viable NEP system design options to develop an understanding of the tasks required to mature critical technologies
- Technology maturation solutions should
 - Take advantage of recent and ongoing investments
 - Where feasible, advance a strategy that aligns with industry participation and identify key areas for such alignment and collaboration

- **Simpler options may win out over higher performing options**
- **Other factors to consider: manufacturability, operability, testability, cost, industry alignment, other investments**

What is a Nuclear Electric Propulsion System?



Recent Findings Related to Nuclear Propulsion

Recent non-advocate studies indicate significant technology investment is needed to overcome low technology readiness for critical subsystems

- National Academies of Science, Engineering, and Medicine¹: Low and intermittent investment in NEP makes it unclear if critical subsystems can be developed to meet a NASA mission with timeline ~ 20 years
- NASA's Engineering & Safety Center: Most of the critical technologies are relatively immature, especially at the system level and the degree of difficulty to make advancements is considered high



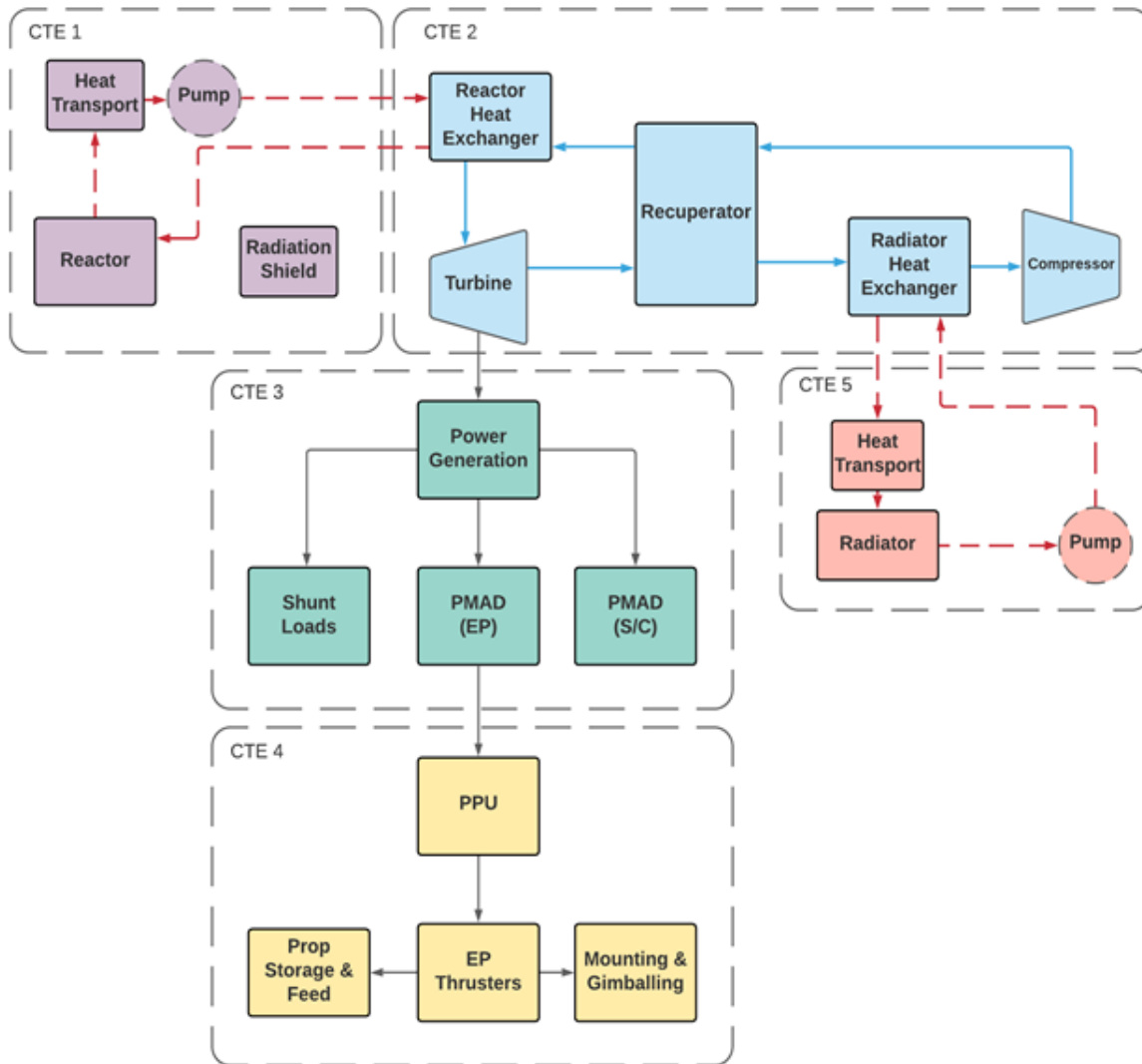
Mission Studies

- Past and recent mission studies for NEP-powered human Mars missions put the required thruster power throughput on the order of MW_e for a duration of 2-3 years
 - Possibly lower power and longer duration for deep space science missions
- For the given readiness levels of the technologies, this order of magnitude power number is sufficiently refined to start technology development and maturation

STMD Nuclear Propulsion Plan must be responsive to the recommendations of recent high-level independent reviews for future NASA mission needs

¹ "Space Nuclear Propulsion for Human Mars Exploration," National Academies of Sciences, Engineering, and Medicine, 2021.

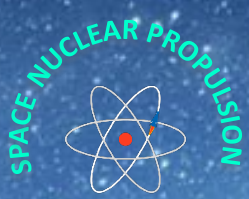
NEP System Overview



- NEP system broken into 5 Critical Technology Elements (CTE)
- Each CTE is further divided into assemblies and components
- Depending on design choices not all items shown will be needed

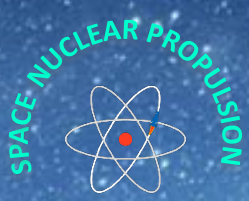
Other technologies of interest

- Chemical Prop System
- Cryogenic Storage of Propellants
- In-space integration, assembly, and fueling



Identifying high-confidence NEP system design options

- Collected available literature on high power EP systems and nuclear electric power generation (was no single repository of source literature)
 - Systems for Nuclear Auxiliary Power (SNAP) [1960s]
 - Space Exploration Initiative [mid-1990s]
 - Space reactor Prototype (SP-100) [mid-1990s]
 - Jupiter Icy Moons Orbiter (JIMO)/Project Prometheus [mid-2000s]
 - Many additional works spread over the past six decades
- Cast a wide net to identify technology options
 - Options not previously available or previously rejected by past NEP projects
 - e.g., HALEU fuel (vs. HEU), high heat flux heat pipes, in-space assembly methods
 - Options under development by other programs / projects that might be applicable to NEP
 - e.g., Electric aircraft power systems, terrestrial microreactors



Identifying high-confidence NEP system design options

- Engagement with technologists and subject-matter experts (SME) to assess technology options
 - Individual one-on-one discussions across the spectrum of Government, Industry, and Academic experts
 - Multiple Technical Interchange Meetings to gain SME input on the current SOA
 - JANNAF Workshop on Flight Qualification Requirements for NTP- and NEP-Powered Human Mars Missions
 - Can we make design decisions that make it easier (or possible) to perform ground testing of a full NEP system for qualification / certification purposes?

CTE 1: Nuclear Reactor

Challenges

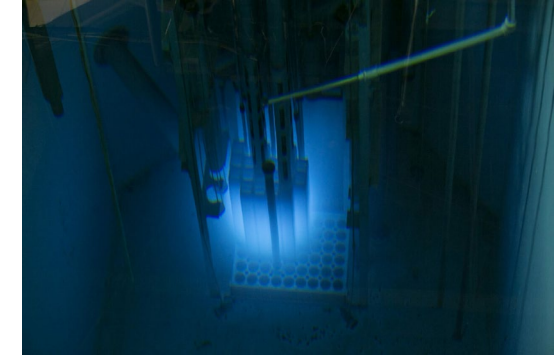
- Lifetime
- Fuel and moderator materials temperatures (coolant at 1200 K or above – higher T, generally smaller radiator)
- Thermal transport
- Internal Pressure* (* mainly issue for direct gas)

Options

- Heat pipe, direct gas, or pumped liquid metal thermal transport
- HALEU (< 20% enrichment) UO_2 , UN, particle-based/micro-engineered fuels
- Be-based, Hydride moderators

Preliminary results

- UO_2 w/Be-based moderator may be sufficient for NEP
 - more complex options like UN or TRISO may not be necessary
- A heat pipe reactor may have sufficient heat transport at low relative reactor mass to support multi-MW NEP (passive, low P)



Missouri S&T nuclear reactor

Figures of Merit		Performance			Readiness		Design Confidence			
Sub-Elements		Power	PCIT	Alpha	Fuel	Moderator	Insulation	Margins	Robustness	GND
UO ₂ -Based Fuel	UO ₂ -BeO	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements
	UO ₂ -Be ₂ C	Exceeds Requirements	Exceeds Requirements	Meets Requirements	Exceeds Requirements	Marginally Meets Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements
	UO ₂ -YH _{1.7}	Exceeds Requirements	Meets Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements	Marginally Meets Requirements	Exceeds Requirements	Meets Requirements	Meets Requirements
UN-Based Fuel	UN-BeO	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements	Meets Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements
	UN-Be ₂ C	Exceeds Requirements	Exceeds Requirements	Meets Requirements	Meets Requirements	Marginally Meets Requirements	Exceeds Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements
	UN-YH _{1.7}	Exceeds Requirements	Meets Requirements	Exceeds Requirements	Meets Requirements	Marginally Meets Requirements	Marginally Meets Requirements	Exceeds Requirements	Meets Requirements	Meets Requirements
Particle-Based Fuel	AGR-TRISO	Does Not Meet Requirements	Does Not Meet Requirements	Does Not Meet Requirements	Meets Requirements	Meets Requirements	Meets Requirements	Meets Requirements	Meets Requirements	Meets Requirements
	MEP-BeO	Meets Requirements	Meets Requirements	Marginally Meets Requirements	Does Not Meet Requirements	Exceeds Requirements	Exceeds Requirements	Marginally Meets Requirements	Exceeds Requirements	Marginally Meets Requirements
	MEP-Be ₂ C	Meets Requirements	Meets Requirements	Marginally Meets Requirements	Does Not Meet Requirements	Marginally Meets Requirements	Exceeds Requirements	Marginally Meets Requirements	Exceeds Requirements	Marginally Meets Requirements
	MEP-YH _{1.7}	Meets Requirements	Meets Requirements	Marginally Meets Requirements	Does Not Meet Requirements	Marginally Meets Requirements	Marginally Meets Requirements	Marginally Meets Requirements	Meets Requirements	Meets Requirements

Analytical hierarchy results for a lithium heat pipe reactor – from “Application of the Analytical Hierarchy Process for Narrowing Down NEP Candidate Reactor Designs,” Rao *et al.*, in *JANNAF Propulsion Meeting*, June 2021.

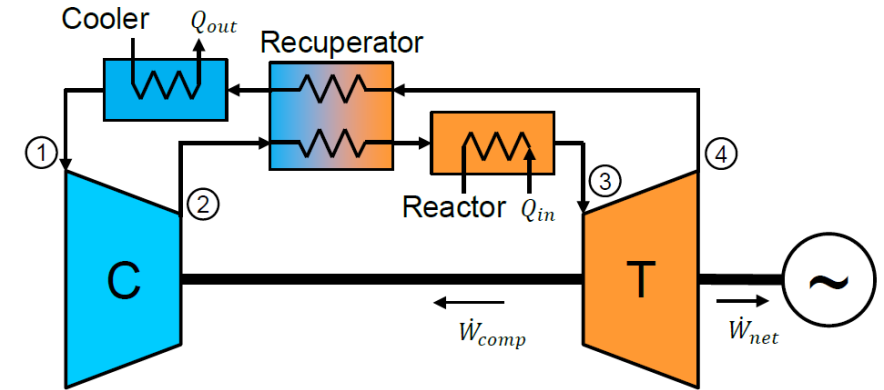
CTE 2: Dynamic Power Conversion

Challenges

- Lifetime
- Efficient power extraction
- Inlet and heat exchanger materials temperatures
- Heat Exchanger Creep
- Compatibility with Reactor and Radiator needs
- Capability to handle transients

Options and Issues

- Several thermodynamic cycle-based conversion systems, but closed-cycle Brayton scales best for MW_e power levels
- He-Xe mixture working fluid
 - Noble gas mixture, systems implications well-understood for the space application, operated in ground test at up to 1200 K, has not operated at MW_e power levels, larger/heavier turbomachinery
- Supercritical CO_2 working fluid
 - Higher pressures ($\sim 7\text{-}20$ MPa), systems implications not well-understood for the space application, lighter turbomachinery, operated in ground test at MW_e power levels, has operated only up to 925 K, molecular dissociation and corrosion properties not well understood at high temperatures, best performance requires compressor inlet at or near critical point (~ 304 K) $\rightarrow$ potentially large/cold radiator



Schematic of a closed-cycle Brayton power conversion system

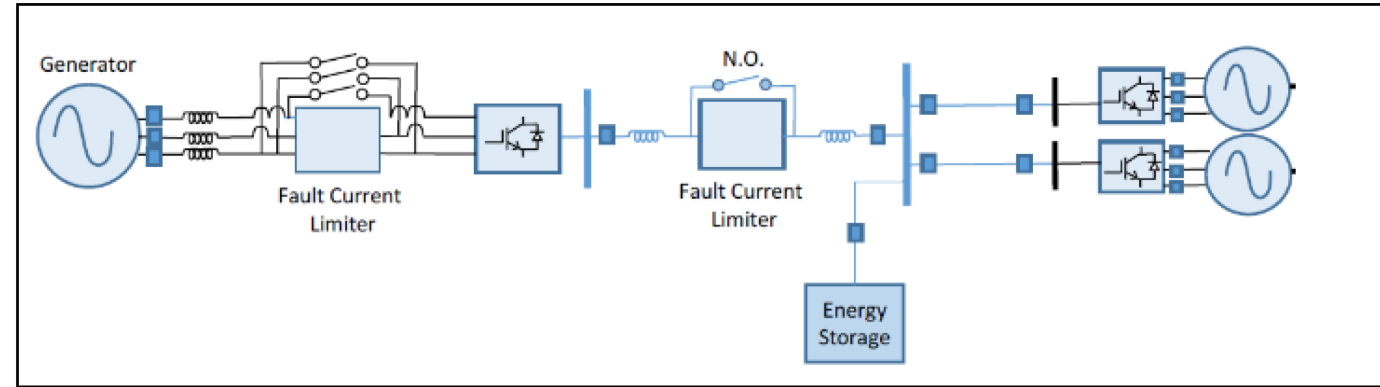
CTE 3: Power Management and Distribution

Challenges

- Lifetime
- Efficient Power Generation
- Minimize distribution currents
- Isolation between thrusters, keep thruster transients from rippling back to the reactor and power conversion system (Capability to handle transients)

Options (partial list)

- Fully Superconducting
- Partially Superconducting
- Permanent-magnet Synchronous
- Single-fed Induction
- Double-fed Induction
- 3ph at $\geq 500\text{kW}$
- Generate $> 1000\text{Volts}$
- Output frequency is determined by the speed and number of poles



Schematic of an electrical power generation system

Possible Trades

- AC vs DC
- Feeder paralleling to optimize distribution
- Incorporating cross ties to improve system reliability
- Component evaluation components (GaN technologies, high power switchgear)

Systems Analysis

- Power Quality (Steady State, Abnormal Operation, Stability, Ripple Voltages and Currents, Fault Clearing)

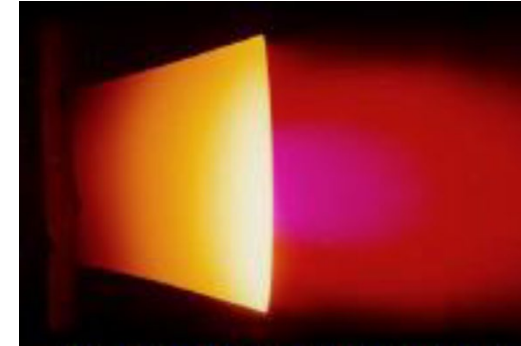
CTE 4: Electric Propulsion System

Challenges

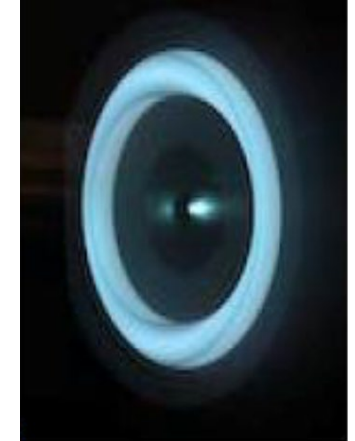
- Lifetime
- Power throughput in a reasonably-sized package
- Stable operation
- Ground testability – correlation with flight data
- Power Processing Unit (PPU) design and components availability

Options and Issues

- Lithium-fed MPD thruster
 - 1 MW thrusters (est. $T \approx 30$ N, $I_{sp} \approx 4400$ s)
 - electrode lifetime, propellant feeding of a liquid metal, low pressure Li-liquid storage, relatively easy to condense/pump in a modest vacuum facility, PPU topology potentially leverages past high current thruster developments, very high current – isolation required between multiple thrusters
- Xenon-fed Hall thruster
 - 100 kW thrusters ($T \leq 5.4$ N, $I_{sp} \leq 3000$ s)
 - cathode lifetime, high pressure (supercritical) Xe-gas storage in large tanks, relatively difficult to condense/cryopump in even a very large vacuum facility, Direct-Drive Unit (DDU) PPU topology never before fabricated/tested – should be easier than present DC-DC Hall thruster PPU, regulated discharge voltage – isolation required between multiple thrusters



200 kW MAI Li-MPD



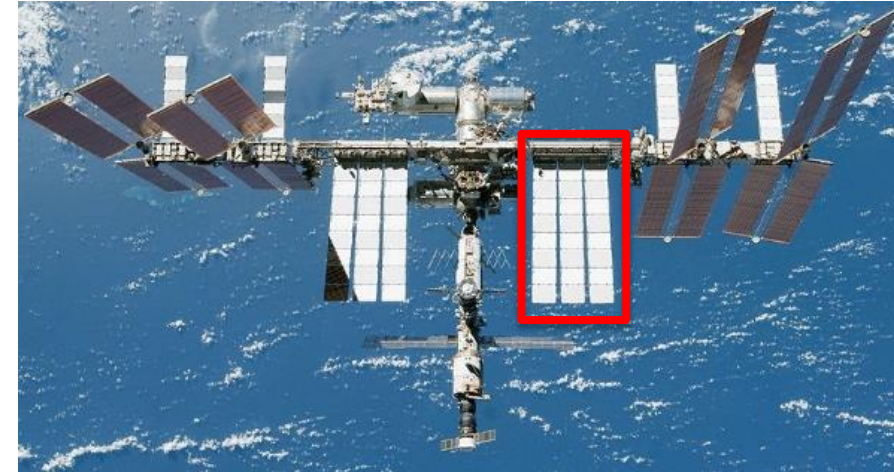
50 kW NASA-457M v2 Xe-Hall

Challenges

- Performance degradation / damage over time / changing thermal environ.
- Deployment and/or assembly
- Efficient heat rejection to space
- Thermal transport and coupling to evenly spread heat on panels

Main Issue

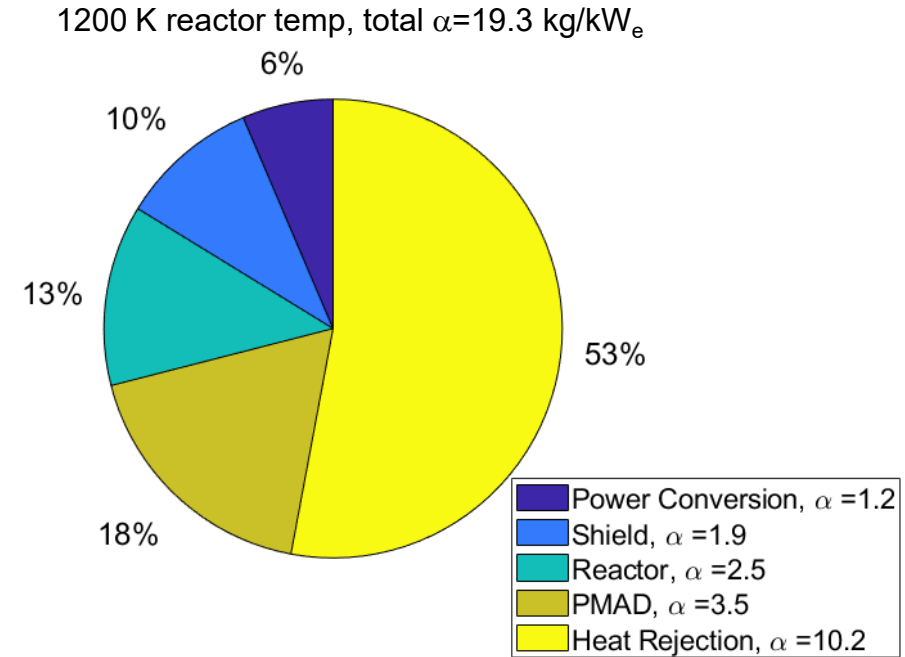
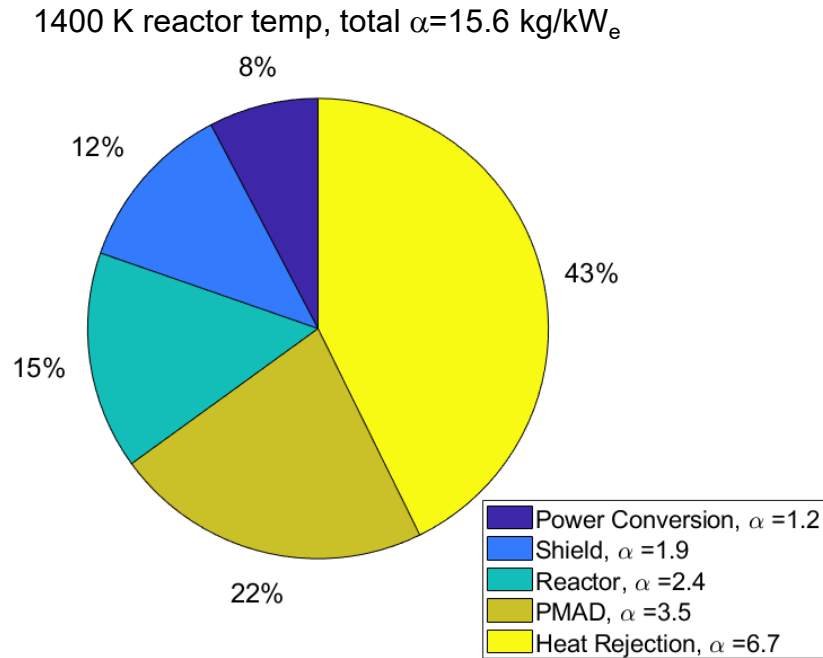
- Radiators as the 'cold side' of the power conversion system
- Heat rejection to space $P = \epsilon \sigma A (T_{rad}^4 - T_{background}^4)$
 - Desire a high radiator temperature
 - Even if the hot side of the thermodynamic cycle can be driven hotter, T_{rad} is not extremely hot for turbomachinery-based power generation (300-600 K, 'low quality' heat – hard to reject to space)
 - Lower quality heat rejection drives to high radiator area A (large power system mass & α [specific mass] driver)
 - Also require high emissivity ϵ (coatings that can last a long time without degradation in the space environment)



ISS External Active Thermal Control System (EATCS) highlighted

Bringing It All Together

Power System Mass Rollup (2 MW_e system)



- Radiator (Heat Rejection) is the largest contributor to system mass
- Increasing reactor operating temperature reduces both radiator mass and overall power system mass
- These modeling results and overall CTE and system lifetime must be validated by test data – technology maturation effort
- As technologies mature, input to the model must be refined (significant uncertainty in present inputs)
- How much above 1200 K can reactor temperature be raised before it represents a major development risk?

