Critical Development Challenges and Potential Advancement Paths for Megawatt-Scale Nuclear Electric Propulsion Systems

Lecture to the Michigan Institute for Plasma Science and Engineering

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NASA – George C. Marshall Space Flight Center

Space Nuclear Propulsion (SNP) Project

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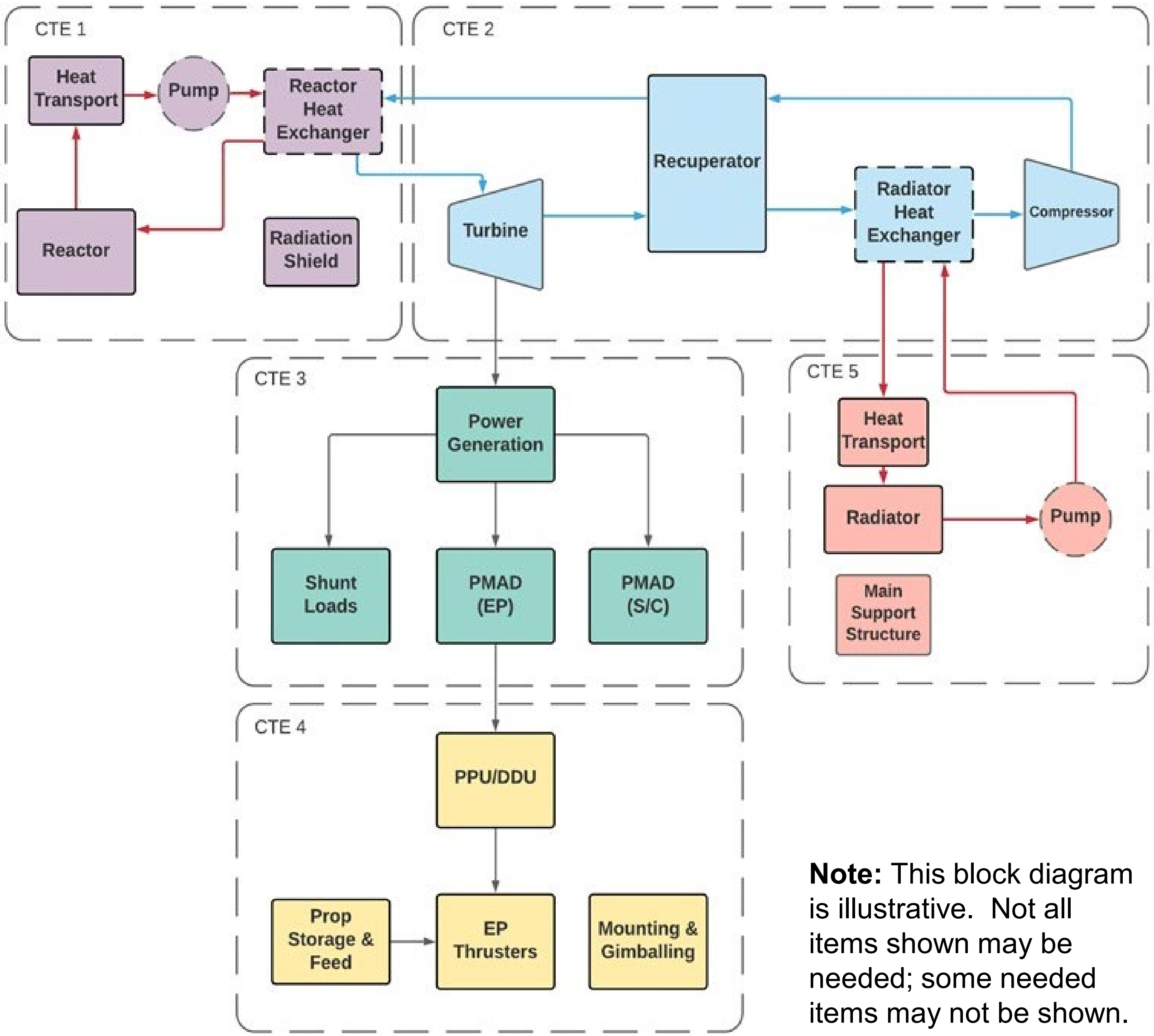
Nuclear Electric Propulsion (NEP): Introduction

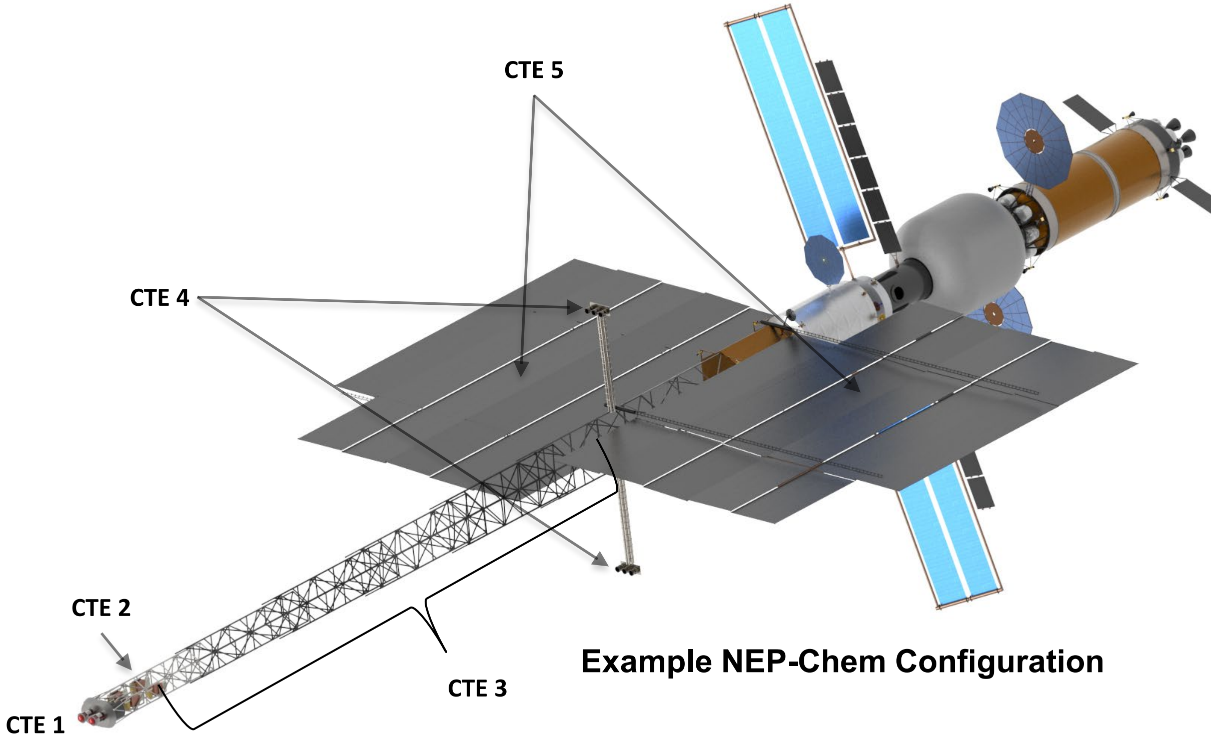


Note: This block diagram is illustrative. Not all items shown may be needed; some needed items may not be shown.

Nuclear reactor heat → Electricity → Electric thrusters

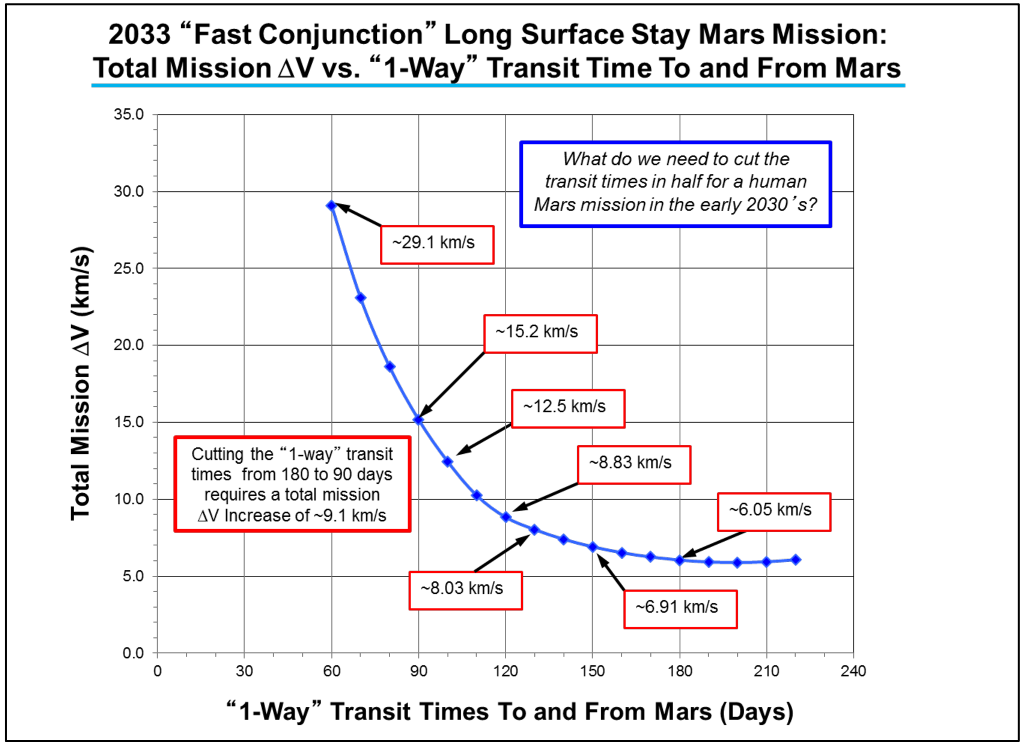
System Critical Technology Elements (CTEs):

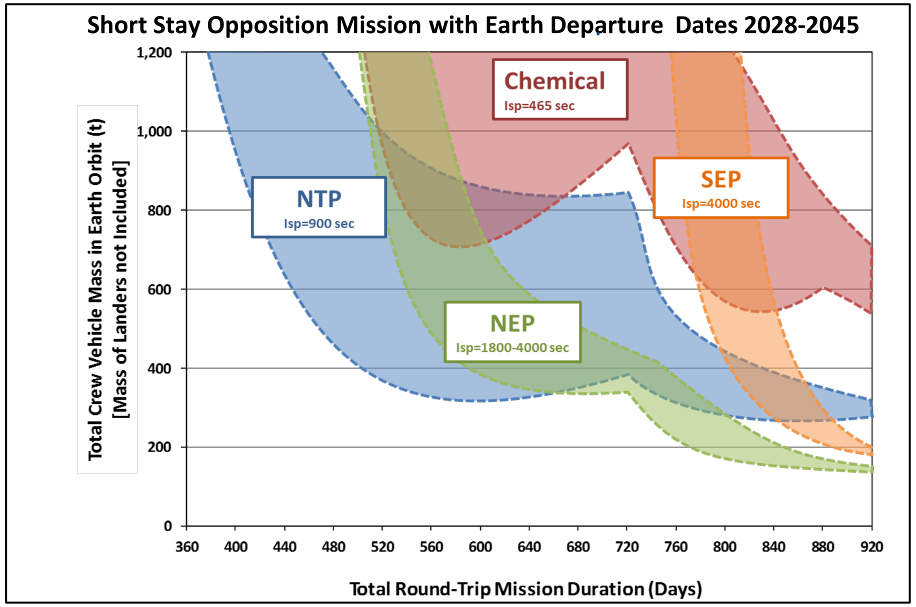
- CTE 1: Reactor and Coolant Subsystem (RXS)
- CTE 2: Power Conversion Subsystem (PCS)
- CTE 3: Power Management & Distribution (PMAD) Subsystem
- CTE 4: Electric Propulsion Subsystem (EPS)
- CTE 5: Primary Heat Rejection Subsystem (PHRS)



Example NEP-Chem Configuration

Why Nuclear Propulsion for Human Missions to Mars?



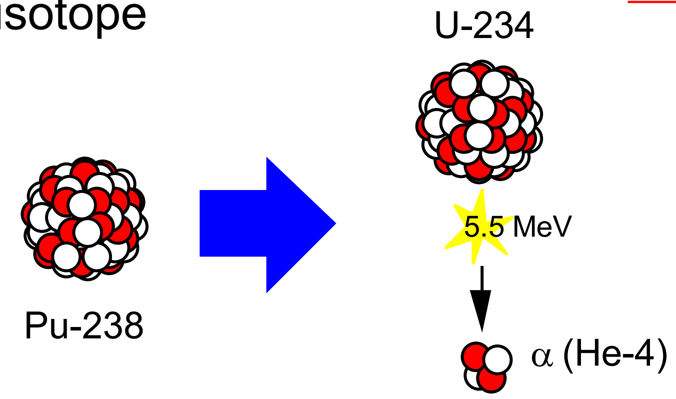


- High Delta V capability → potential shorter trip time (reduce exposure to galactic cosmic radiation and zero-g)
- Mission robustness and potential abort scenarios
- Fewer rocket launches → save time and $$$
- Huge potential for growth over current capabilities

Fission-based – Different from Previous NASA "Nuclear"

Radioisotope

Launched 'hot'



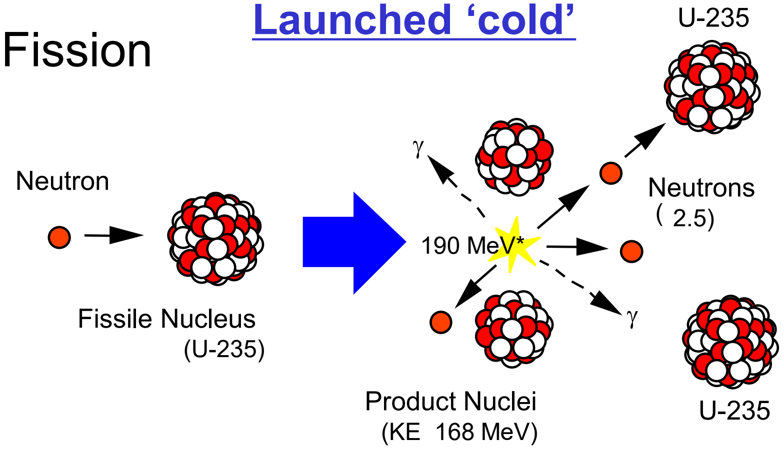
Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

Natural decay rate (87.7-year half-life)

- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Long history of use by US
  - 44 Radioisotope Thermal Electric (RTGs)
  - 100s of Radioisotope Heater Unit (RHUs)
- Thermal management and electricity

Fission

Launched 'cold'



Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate (variable power levels)

- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
- Heat converted to electricity or used to directly heat a propellant
- Used terrestrially for over 70 years
- One flow US space power reactor (SNAP-10A) (1965)
- TOPAZ reactors flown by USSR

Current Status of NEP According to Recent Independent Reviews

- **2020 - NASA Engineering and Safety Center (NESC) study findings:**
  - "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."
- **2021 - National Academies of Science, Engineering, and Medicine panel report findings:**
  - "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."

Challenge #1: High Assay Low-Enriched Uranium (HALEU)

- Lower proliferation/security risks → Lower project cost
- Allows broader engagement of expertise
- Aligns with other projects developing systems to use LEU
- Higher mass than HEU systems

Initial Moderated LEU (< 20%) Conceptual Designs Very Promising

- Consistent with US policy. “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.” (2012 White House “Fact Sheet”)
    - Space Policy Directive 6 also mandates use of LEU in most cases
    - National Security Presidential Memoranda (NSPM) 20 – Rules governing launch approval authority

Can Space Nuclear Systems Using Low-Enriched Uranium (LEU) be Developed?

High-Profile HALEU Nuclear Projects

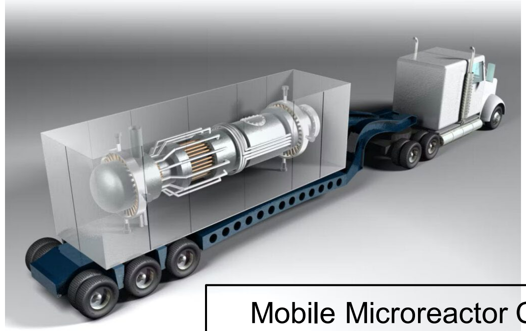
For In-Space Use

- NASA Space Nuclear Propulsion (SNP) (NTP and NEP)
- NASA Fission Surface Power (FSP) (10s kW_e)
- DARPA Demonstration Rocket for Agile Cislunar Operations (DRACO) (NTP)
- AFRL/USSF Joint Energy Technology Supplying On-Orbit Nuclear Power (JETSON) (NEP) (10s kW_e)

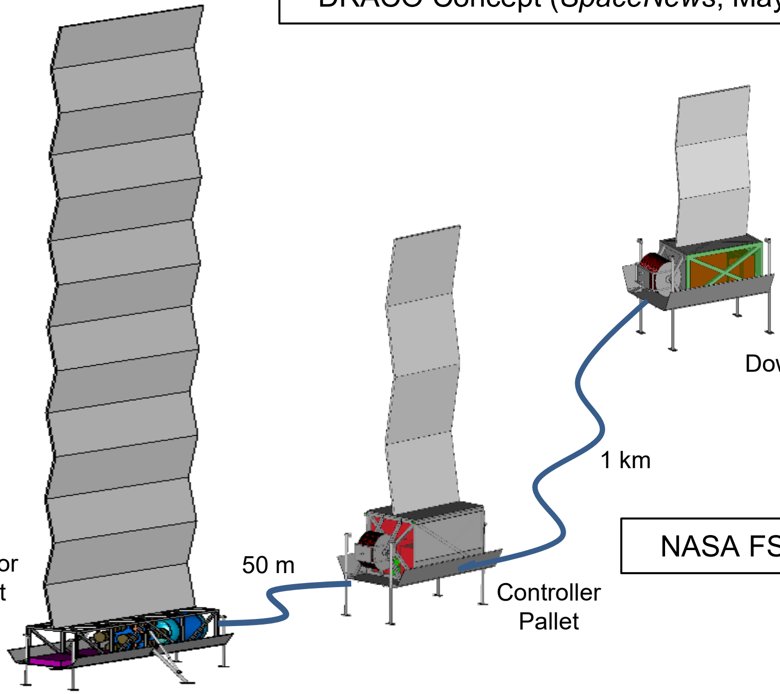
DRACO Concept (*SpaceNews*, May 2022)

For Terrestrial Use

- DOE and Commercial Terrestrial Microreactors (10-20 MW_e)
- DOD Strategic Capabilities Office (SCO) Project Pele (1-5 MW_e)



Mobile Microreactor Concept (*PowerMag*, April 2022)

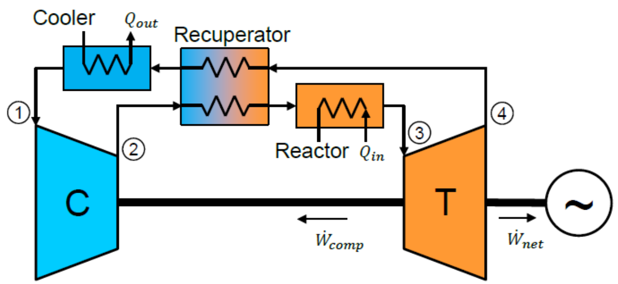


NASA FSP Concept

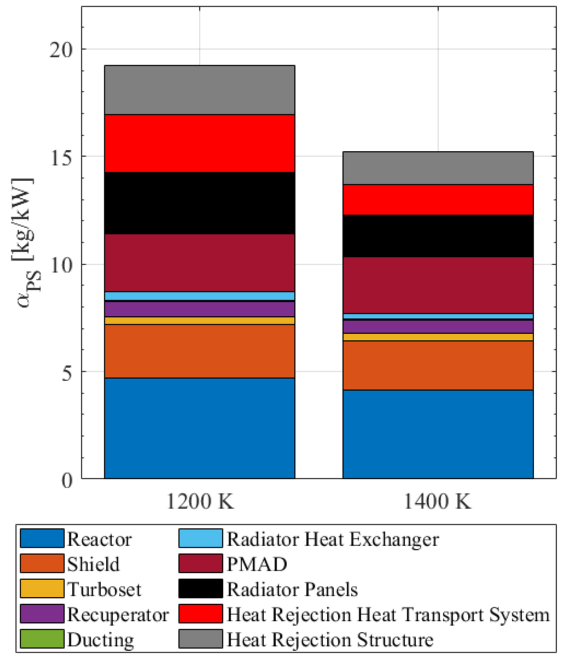
Challenge #2: NEP Power System

<u>≥ 25,000 hours of continuous operation</u>

- Reactor
  - Similar to terrestrial, but **hotter**
  - Not as hot as NTP
- Power Conversion
  - Closed cycle
  - Want a hot inlet
  - <u>Don't want highest possible efficiency</u>
- Heat Rejection (Radiators)
  - $P = \epsilon\sigma A\left(T_{rad}^4 - T_{background}^4\right)$
  - Want lightweight radiator at high temperature and emissivity



Closed Brayton Cycle Power Generation System



2 MW_e gas cooled reactor mass breakdown for PCIT of 1200 and 1400 K

Harnack *et al.*, *AIAA ASCEND*, 2022. AIAA 2022-4288

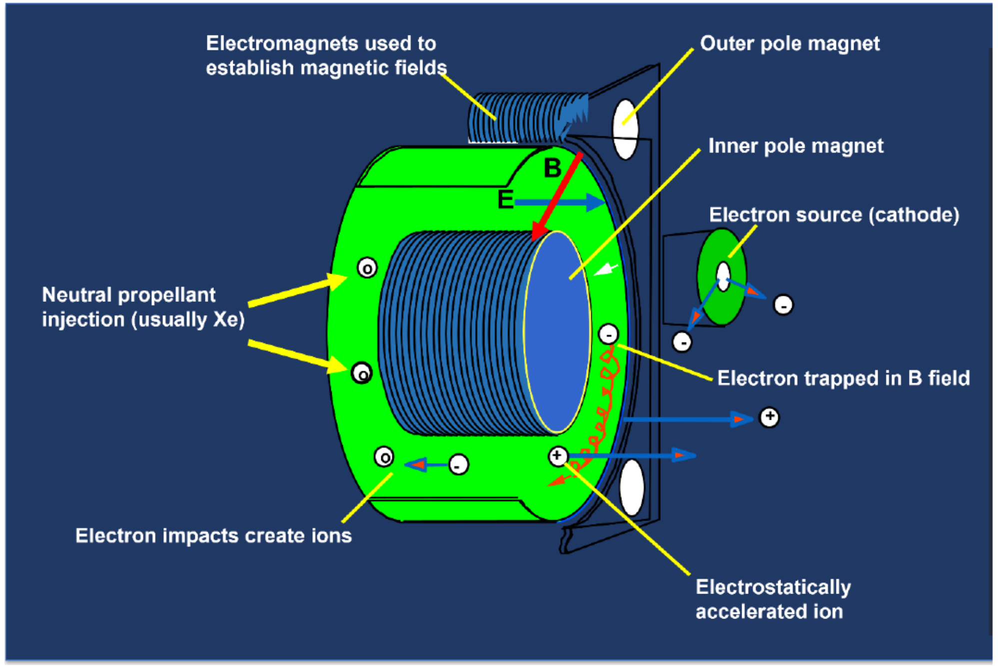
Radiators are largest, heaviest component of NEP system – reduce overall system mass at higher T

Challenge #3: Electric Propulsion System (Hall Thruster)

NEP Propulsion Requirements

- ≥ 20,000-30,000 hours of continuous operation
- Multi-MW_e power throughput
- No flight experience at 10 kW_e or above

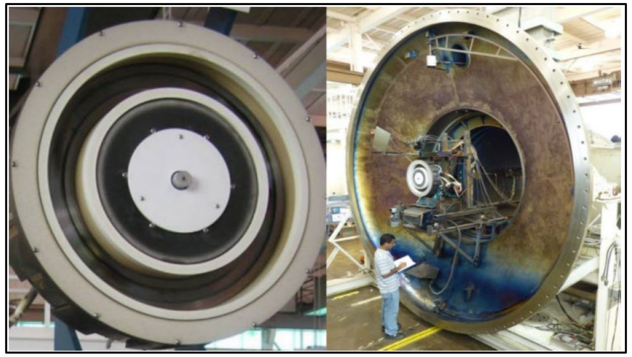
- **Hall Thruster (Xe-fed)**
  - ~5 kW_e operational flight systems
  - 12.5 kW_e AEPS for Gateway/PPE (not yet flown)
  - Brief ground tests at 100 kW_e on large lab-model thrusters
  - Relatively massive (magnetic circuit materials)
  - Difficult to pump Xe



Conceptual Hall Thruster Schematic

Challenge #3: Electric Propulsion System (Hall Thruster)

- **Hall Thruster (Xe-fed)**
  - **Challenges**
    - Multi-thruster high-power thruster plume and spacecraft interactions / facilities impacts – validity of ground test data
    - Simultaneous operation of multiple thrusters in proximity and at power
    - Power Processing Unit / Direct-Drive Unit (high power w/AC input)
    - Cathode lifetime (very high currents … >> 100 A emission)
    - Thruster size / stock materials availability
    - Xe-propellant storage (high-pressure supercritical or cryogenic)



NASA-457 v2 Hall Thruster

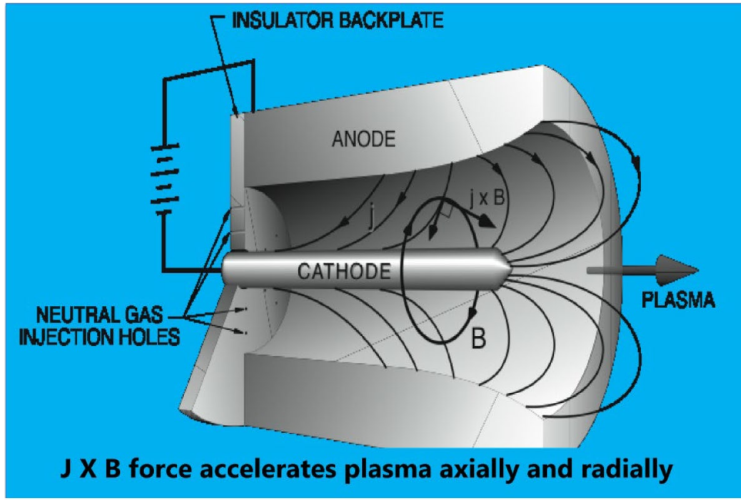
U of M Nested Hall Thruster

Challenge #3: Electric Propulsion System (MPD Thruster)

NEP Propulsion Requirements

- ≥ 20,000-30,000 hours of continuous operation
- Multi-MW_e power throughput
- No flight experience at 10 kW_e or above

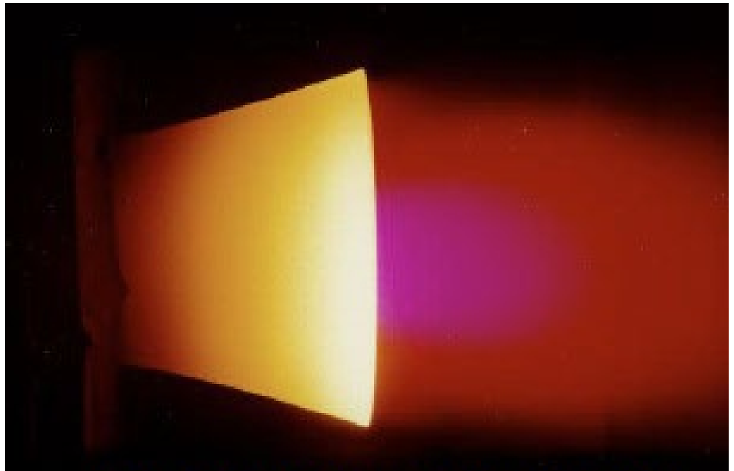
- **Magnetoplasmadynamic (MPD) Thruster (Li-fed)**
  - No operational flight systems
  - Ground tests up to 500 kW_e at 500 hours on a lab-model thruster (minimal cathode erosion)
  - Inherently high-power thruster
  - Test facility cold-wall 'pumping'



Conceptual MPD Thruster Schematic

Challenge #3: Electric Propulsion System (MPD Thruster)

- **Magnetoplasmadynamic (MPD) Thruster (Li-fed)**
  - **Challenges**
    - Long-duration cathode lifetime
    - Anode degradation (avoiding spot-mode discharge / ‘onset’)
    - Power Processing Unit at scale (high power w/AC input)
    - High-current transients on start-up / shut-down
    - Limited performance database



200 kWe MAI Li-MPD Thruster

Final Takeaways

NASA and DOE collaborating with industry and academia on SNP development efforts

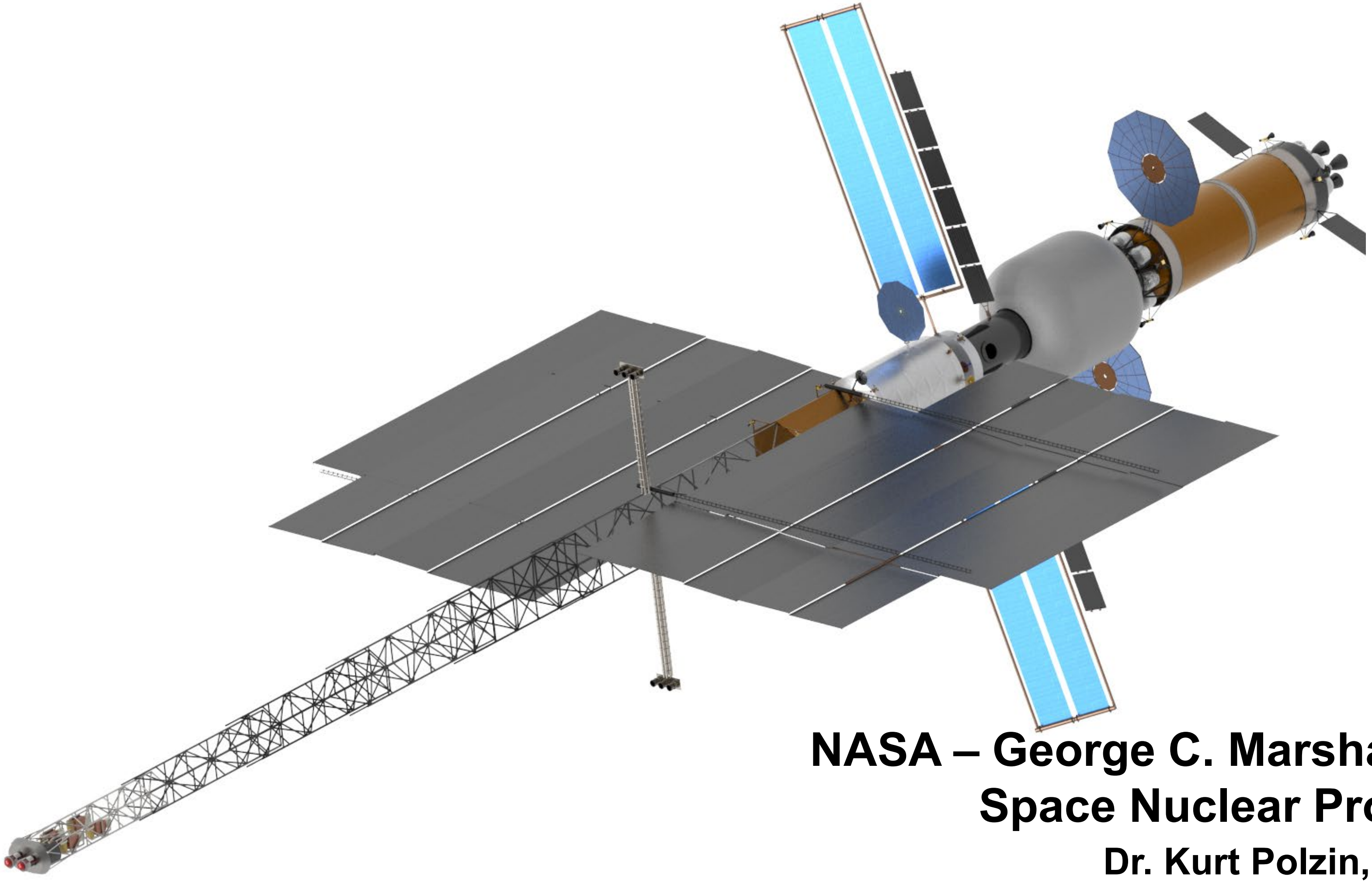
NEP Efforts

- Government-developed technology maturation plan to guide project direction and investments
- Multiple parallel development options to mature key technologies and systems
- Build and test hardware at relevant conditions (e.g., temperatures, power levels, 1 MW_e building blocks)

- HALEU fuel form opens door for increased participation (vs. HEU)
- Take advantage of recent and ongoing multi-agency nuclear investments
- Advance strategy that aligns with industry participation
  - Including technologies not initially developed for space nuclear applications (electric aircraft, ground-based reactor designs and modeling tools)

Work represents a broad national effort to develop the technologies and systems for Space Nuclear Propulsion and show those systems can be realized.

Questions



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