EXPLORE SPACE TECH

Space Nuclear Technology Portfolio Update

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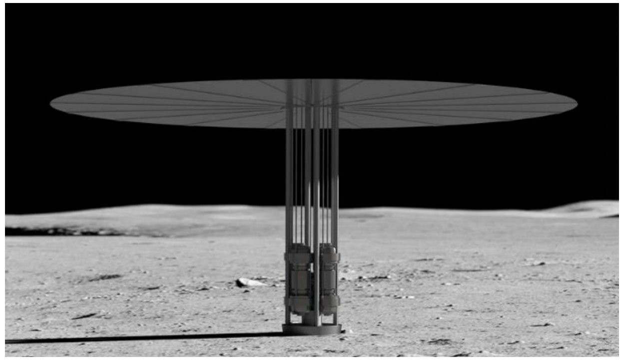
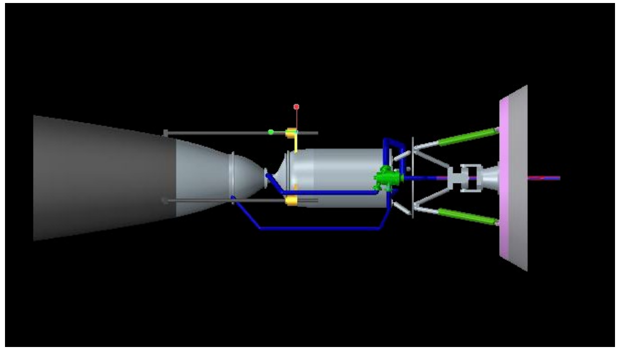
Space Nuclear Technology Portfolio Summary

NASA STMD Space Nuclear Technology investment focuses on advancing fission power and propulsion capabilities that enable future exploration missions

- **Fission Surface Power (FSP)** Design and build an evolvable fission surface power system, and demonstrate the capability on the lunar surface before 2030
  - Promote industry engagement, new innovations, and commercial ownership

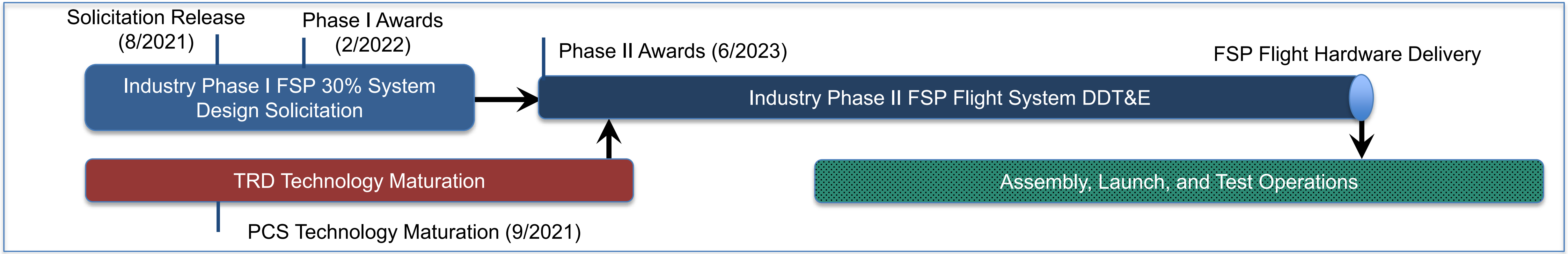


- **Space Nuclear Propulsion (SNP)** Advance a fast transit, in-space, nuclear propulsion system and demonstrate a mission relevant flight capability
  - Team with relevant government and industry organizations - DARPA DRACO



NASA and DOE are advancing low enriched uranium reactor solutions for Space Power and Propulsion

FSP Development Plan



FSP Project Impacts

- Budget constraints limited FY21 funding ($8M) and resulted in a significant de-scope of planned activities
- COVID quarantine restricted facility (laboratory and test facility access

FSP Project Accomplishments

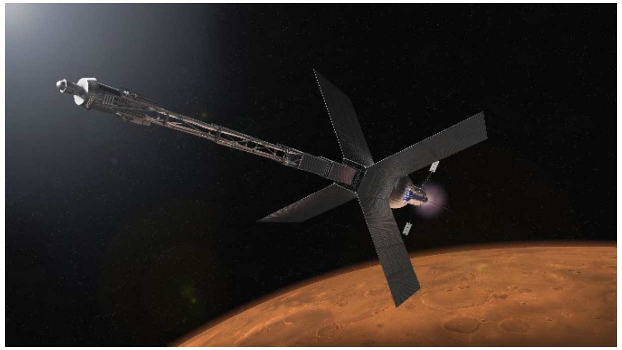
✓ (3/2020) Moderated HALEU reactor design concepts completed showing ~15% mass penalty
✓ (7/2020) Release request for information for FSP system design
✓ (12/2020) Release draft SoW for Phase I FSP 30% design effort
✓ (3/2021) Test reference design assessment of PCS configuration and fault tolerance

Space Nuclear Propulsion

NASA STMD nuclear propulsion technology investment is focused on advancing a fast-transit, deep-space propulsion capability

Nuclear Electric Propulsion System

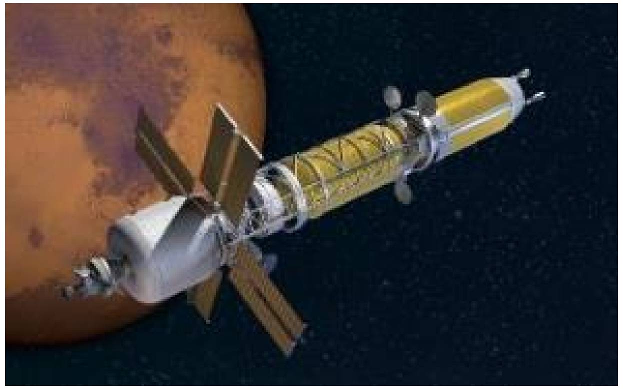
- Current Agency reference configuration for Mars transportation system
- Internal architecture and capability studies are being used to identify a technology maturation plan and project formulation effort



NEP vehicle concept

Nuclear Thermal Propulsion System

- Capability has had several years of active technology investment with a focus on a high temperature reactor design
- Currently funding inter-agency collaborations for fuel fabrication (DOD/SCO), reactor materials (DOE), and flight system development (DARPA/DRACO)
- Robust industry engagements which include advanced fuel production, reactor design, and cryogenic fluid management

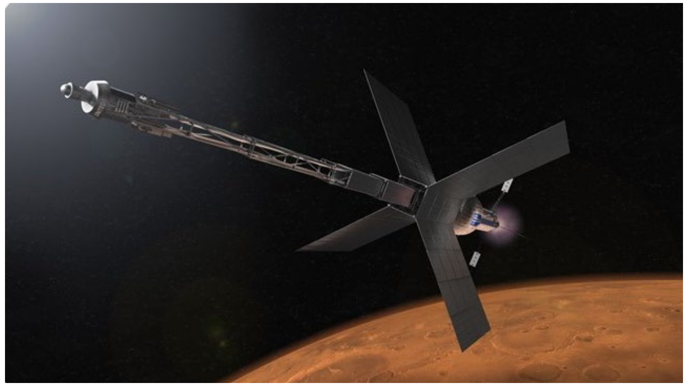


NTP vehicle concept

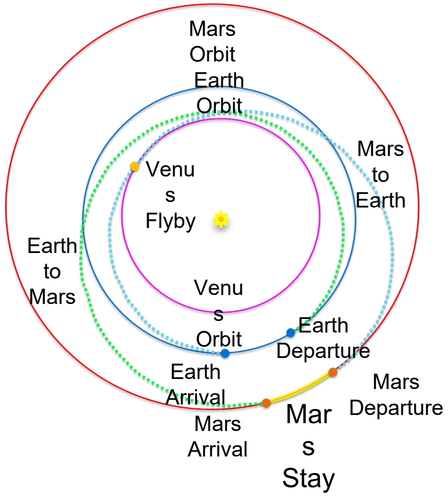
Nuclear Propulsion Opposition Class Mission

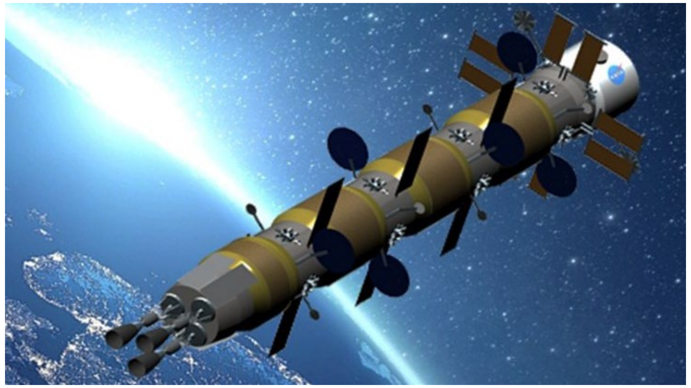
Note: FY2022 President's Budget Request does not include funding for nuclear propulsion

NASA baseline Mars short-stay (~750-day) mission architecture

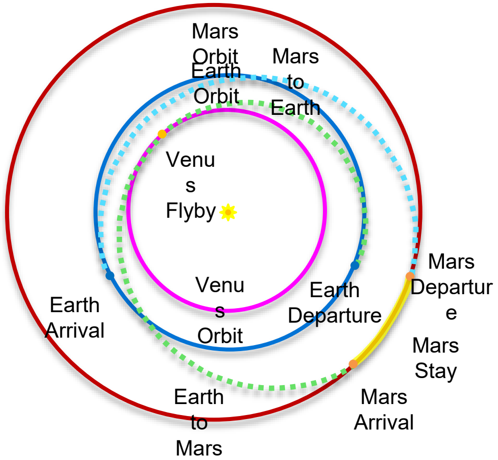


Nuclear Electric/Chemical Propulsion





Nuclear Thermal Propulsion

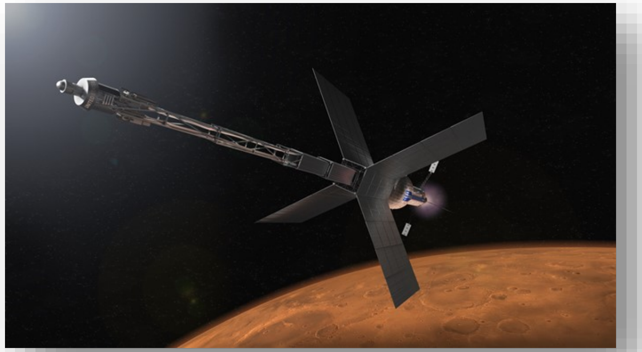


- High propellant efficiency – low thrust system
- Reduced propellant mass and storage requirements
- Potential deep space mission applications

- Reduced propellant efficiency – high thrust system
- Synergy with DOD for cis-lunar operation
- Potential for fast deep space and robotic missions

Nuclear Electric Propulsion

Agency identifying key subsystem state of the art to identify technology gaps, test infrastructure needs, and programmatic risks of implementing a capability formulation project



NEP technology maturation plan considerations need to include:

- Space-rated reactor using high-assay, low enriched uranium (~2 MW_T)
- Brayton cycle power conversion system
- High-power (≥100 kW_E) electric thruster system
- Testing and test infrastructure

Several TIM's were held from December 2020 through April 2021 covering key NEP subsystem capability needs for reactor design, power conversion, electric thrusters, power management, thermal management, and assembly

- Assure planning activity is coordinated with MTAS, participating NASA centers, and other key organization (DOE, DOD, industry and universities)
- Provide a broad community assessment for the SOA and potential advancement requirements for critical capabilities
- Identify execution strategies and that engage external organizations during the early stages of implementation
- Identify collaboration areas and technology maturation paths that leverage existing government and industry capabilities

Plan is to deliver a NEP/Chem technology maturation plan (scope, cost, schedule) that addresses the capability needs for a Mars exploration mission

Nuclear Thermal Propulsion

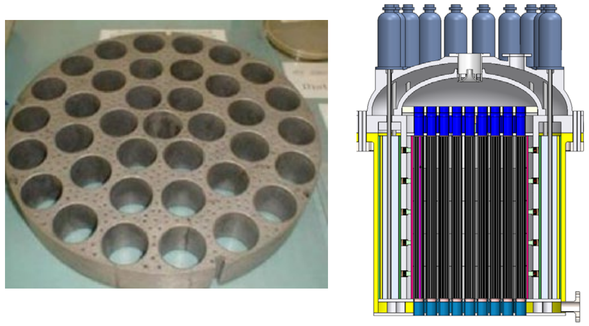
Note: FY2022 President's Budget Request does not include funding for nuclear propulsion

Develop a subscale nuclear engine that demonstrates a viable high I_{sp} capability that is scalable to a Mars propulsion system

NTP implementation considerations include:

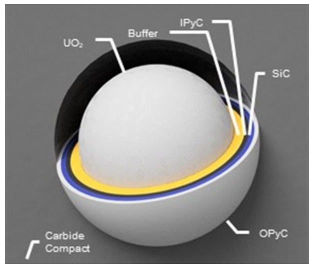
- High assay, low enriched uranium reactor that can provide (250 MW_T @ 2900 K)
- Design and build a subscale engine with 12,500 lbf thrust and 900s I_{sp}
- Engine scaling is an engineering solution without further technology development
- Digital twin model development and test validation

Moderator Block Reactor Core



In January 2020, NTP revised the fuel and reactor technology maturation approach from a pack-powder (fission fuel) cannister approach based on Rover/NERVA to a Topaz moderator block design with solid fission fuel elements

- Technology maturation plan is focused on fuel advancement for sintered ceramic-metal (cermet) and ceramic-ceramic coated carbide fuels
- Diverse development team from NASA, DOE, industry, and university organizations
- Plan for key multi-loads tests with flowing hydrogen demonstrating maturity advancements and functional feasibility
- Complete industry trade studies and solicit industry reactor designs

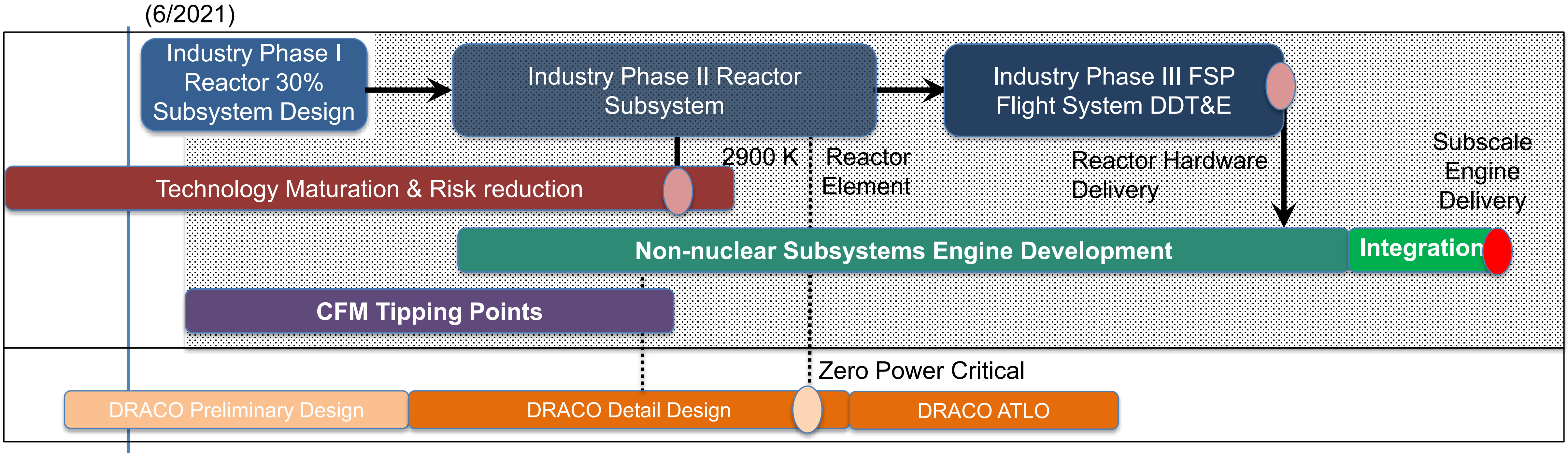


Coated fuel particle

Goal is to deliver an integrated subscale engine for potential future ground or flight demonstration

NTP Subscale Engine Development Plan

Note: FY2022 President's Budget Request does not include funding for nuclear propulsion



Subscale engine development will support ground or flight demonstration

- FY22 President's budget request does not include funding for space nuclear propulsion investments
- Planned decision on flight or ground demonstration is based on engineering value and results from DRACO
- NASA Phase II reactor design and CFM effort have alignment interest with DRACO
- NASA technology maturation effort will inform Phase II Industry efforts

Technical Accomplishments and Issues in 2020

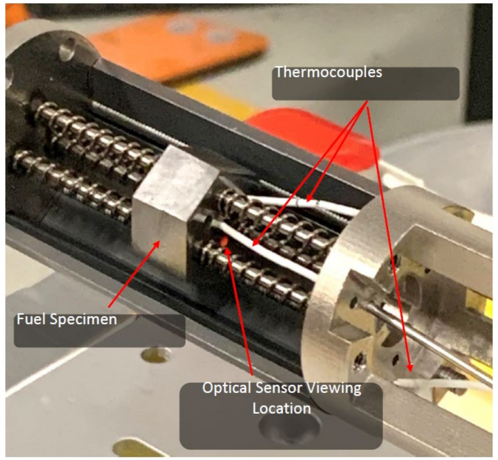
Fuel Development

- ✓ (September 2020) Assembled experiment capsule delivered to INL and integrated into TREAT on schedule for an initial neutron calibration transient
- ✓ (December 2020) Temperature ramp rate testing of cermet fuel specimens under prototypical conditions of ~100 ºC/sec
- ✓ (December 2020) Depleted uranium cermet fuel specimens fabricated and machined into final shape with hydrogen flow holes through the fuel wafers
- ✓ (April 2021) Production of small diameter UN precursor fuel kernels through sol-gel process
- ✓ (May 2021) Sintering of UN cercer fuel wafers completed, and samples transferred to INL for machining and transient thermal test preparation

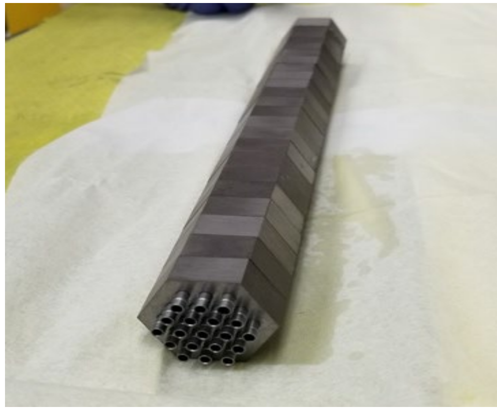
Moderator Development

- ✓ (November 2020) Complex zirconium hydride (ZrH) moderator geometries successfully fabricated
- ✓ (December 2020) Established a powder metallurgy technique for fabricating yttrium hydride (YH) material that can be applied to ZrH fabrication

TREAT experiment configuration



Cermet fuel Element



Technical Accomplishments and Issues in 2020 (Continued)

Hydrogen "Loop" Facility Modification

- ✓ (February 2020) Initial concept defined to support combined-effects fuel testing
- ✓ (October 2020) Conceptual design review (30% fidelity) successfully completed
- ✓ (March 2021) Preliminary Design Review (60% fidelity) successfully completed

DARPA Collaboration

- ✓ (September 2020) Collaborated on DRACO Phase I - Track A and B industry proposal evaluations
- ✓ (April 2021) Participated in kickoff for DRACO Track-B kickoff meetings with Lockheed Martin and Blue Origin
- ✓ (May 2021) Supported DARPA DRACO kickoff meeting with General Atomics

Industry Subscale Reactor Design

- ✓ (July 2020) Completed industry flight reactor trade study and industry design solicitation drafted
- ✓ (February 2021) Released solicitation for Phase-1, 30% fidelity design proposals
- ✓ (June 2021) Industry proposal selections

NASA NEP and NTP Trade Studies

NESC conducted a mission-agnostic assessment of critical technology maturity & gaps

- Key sub-system capability needs for both NEP/Chem and NTP have comparatively equal levels of technology maturity and advancement difficulty

National Academies report “Space Nuclear Propulsion for Human Mars Exploration”

- Majority of the technologies needed for both systems require aggressive development to meet a 2039 Mars mission, and reactor development considered most challenging
- Low and intermittent funding by NASA makes it unclear if a NEP/Chem stage can be ready for a 2039 even with aggressive investment
- NASA needs significant, concurrent investment for both NEP and NTP to support an informed capability down selection

Mars Transportation Architecture Study for a 2039 mission

- NEP architecture requires 40% less launch mass and 70% fewer flight system assembly launches to achieve a human Mars opposition class mission
- Reduced architectural complexity makes NEP the preferred technology pathway for NASA

National Academy Study Findings/NASA Response

Finding 1: A significant amount of characterization of reactor core materials, including fuels, remains to be done before NASA and DOE will have sufficient information for a reactor core design

Agree: NASA, DOE and DOD are actively pursuing a multidisciplined approach to fuel and moderator development to realize a suitable high-temperature fuel that operates at the required temperatures

Finding 2: Long-term liquid hydrogen storage is required at 20 K for NTP baseline missions

Agree: NASA is making significant investments in key technologies including in-space cryocoolers capable of high-capacity refrigeration at 20 & 90 K that enable minimal boil-off for long duration missions

Finding 3/4: Modeling & Simulation, Ground and Flight Testing: Subscale in-space flight testing cannot replace full-scale ground testing; with sufficient M&S *and fully integrated system ground testing*, flight qualification requirements could be met by cargo missions

Agree: Cargo or other in-space missions can be leveraged as a system capability demonstration with modeling and simulation and limited ground testing. Integrated ground and flight testing will be key elements of any for any human-rated system.

National Academy Study Findings/NASA Response

Finding 5: NTP program success - an aggressive program could develop an NTP system capable of executing a baseline mission by 2039

> **Agree:** NASA's next NTP priority would be to pursue solutions to technology challenges for reactor development, hydrogen propellant storage, ground testing, and reactor modeling and simulation

Finding 6: Developing a MWe class NEP system requires orders of engineering scale increase, due to low historical investment, it is unclear if even an aggressive program will be able to develop an NEP system capable of executing baseline mission by 2039

> **Agree:** NASA has not significantly advanced the readiness of key technologies and has recently initiated key NEP technology development planning that will leverage existing industry and government capabilities and investments to buy down risk and schedule

Finding 7: Apples-to-apples trade studies comparing NEP and NTP systems for a crewed Mars mission in general, particularly the 2039 baseline mission, do not exist

> **Agree:** MTAS provided an apples-to-apples mission level trade study comparison. A higher fidelity design trade study with associated technology readiness, and development challenges is needed for NEP and efforts are underway to align with the fidelity for NTP

National Academy Study Findings/NASA Response

Finding 8: Given NEP/NTP key commonalities for significant technology maturation – development work can proceed independently of the selection of a particular space nuclear propulsion system

Agree: Though operating conditions differ, NEP & NTP can leverage similar advancements in fuel form, fuel production, neutron reflector and moderator materials, M&S, and common safety & regulatory requirements

Finding 9: Enrichment of Nuclear Fuels - a comprehensive assessment of HALEU vs HEU for NTP and NEP systems

Partially Agree: NASA/DOE's internal and industry studies to date indicate moderated HALEU nuclear systems provide a viable solution with acceptable mass penalties as compared to an HEU system, given some technology development investments on moderator block designs. National policy changes provided in NSPM-20 and SPD-6 impose significant approval requirements on the use of HEU that favor HALEU solutions and potentially enable industry engagement due to relaxed security. As a result, NASA has listed HALEU solutions as the primary option for the industry studies, but it does not preclude HEU as a consideration.

Finding 10: Synergies with Terrestrial and National Defense Nuclear Systems

Agree: Significant commonalities exist between SNP and compact terrestrial systems (DOD SCO's "Pele" and some industry concepts) and the DRACO program; NASA's close coordination with key agency partners could benefit both NEP and NTP system development

Summary

- ✓ NASA priority focus remains on designing, building, and demonstrating a fission surface power system that is directly applicable for Moon and Mars, scalable to power levels above 100 kw_E, and has potential to advance NEP system needs
- ✓ NASA is working with other government agencies to establish a common technology development roadmap that leverage priorities and resources for advancing space nuclear energy technology
- ✓ NASA will continue to be closely engaged with industry on nuclear technology development
- ✓ NASA will continue to support DARPA DRACO's demonstration mission and other nuclear technology development efforts such as long-term in-space cryogenic fluid management and storage
- ✓ NASA agrees a balanced technology investment posture for both NTP and NEP is needed to inform down-select decisions
- ✓ A nuclear-powered transportation system would be a transformational capability to support human Mars missions which will require a substantial and sustained investment for well over a decade