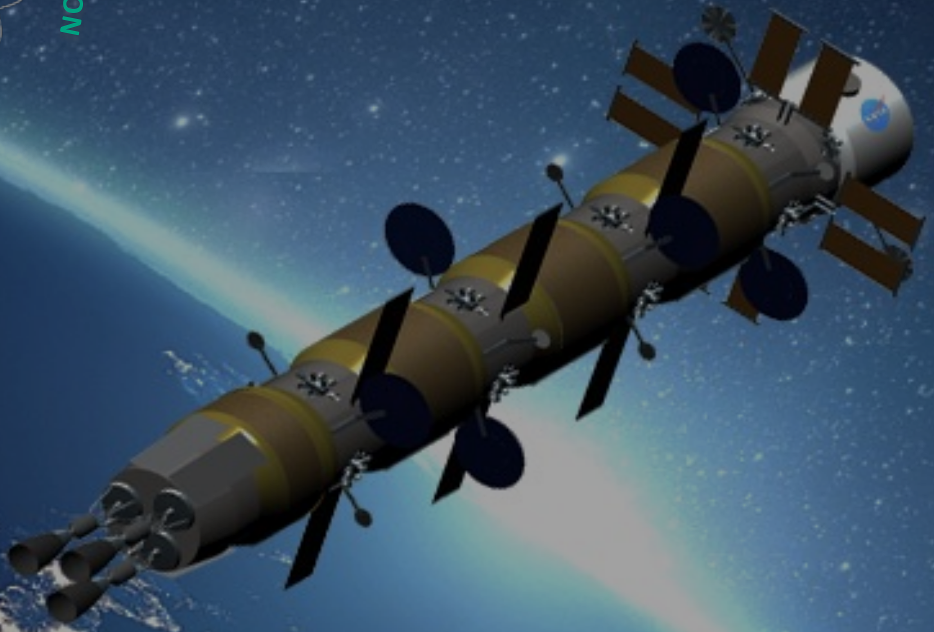


NASA Advisory Council Technology, Innovation, and Engineering Committee

Space Nuclear Propulsion

Dr. Anthony Calomino | Space Nuclear Technology Portfolio Manager | November 30, 2023

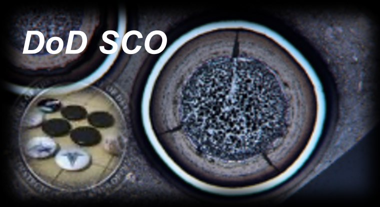
Space Nuclear Propulsion

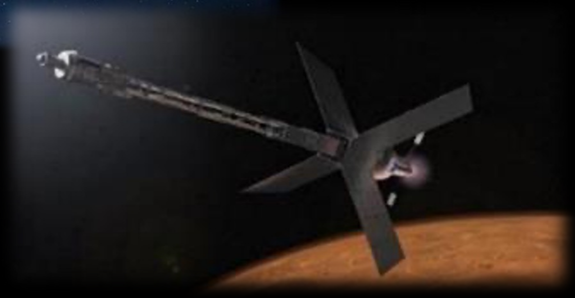
- Provides a robust and reliable energy to human and scientific exploration missions
- Offers energy-dense systems with high ratios of power to mass and volume
- Shares a strong interest from industry and other government organizations for space transportation

Propulsion: Speed, Maneuverability, Resiliency

- High-thrust gravity maneuvers
- Rapid cis-lunar transit
- Robust transportation for Mars human exploration
- Higher value deep-space science missions

Interagency Commonality



Industry Engagements

LOCKHEED MARTIN

USNC ULTRA•SAFE•NUCLEAR

GENERAL ATOMICS

BWXT BWX Technologies, Inc.

Independent Evaluation

FY 2021 NASEM Consensus Report on Space Nuclear Propulsion for Human Mars Exploration Nuclear Electric Propulsion (NEP) and Nuclear Thermal Propulsion (NTP) systems show great potential to facilitate the human exploration of Mars

- Short-stay missions require higher propulsive energy
- Flexibility to launch opportunity is a major advantage of the use of nuclear propulsion
- Concurrent early investments in technology maturation are needed for NEP and NTP
- Early reactor development is key for both NEP and NTP
- NTP reactor and NEP system integration carry the highest risk
- Both systems can meet mission requirements but need aggressive early investments

Artemis Architecture Concept Review (ACR) carries both NTP and NEP as open trade, with a development horizon spanning at least 10 years

Congressional Direction

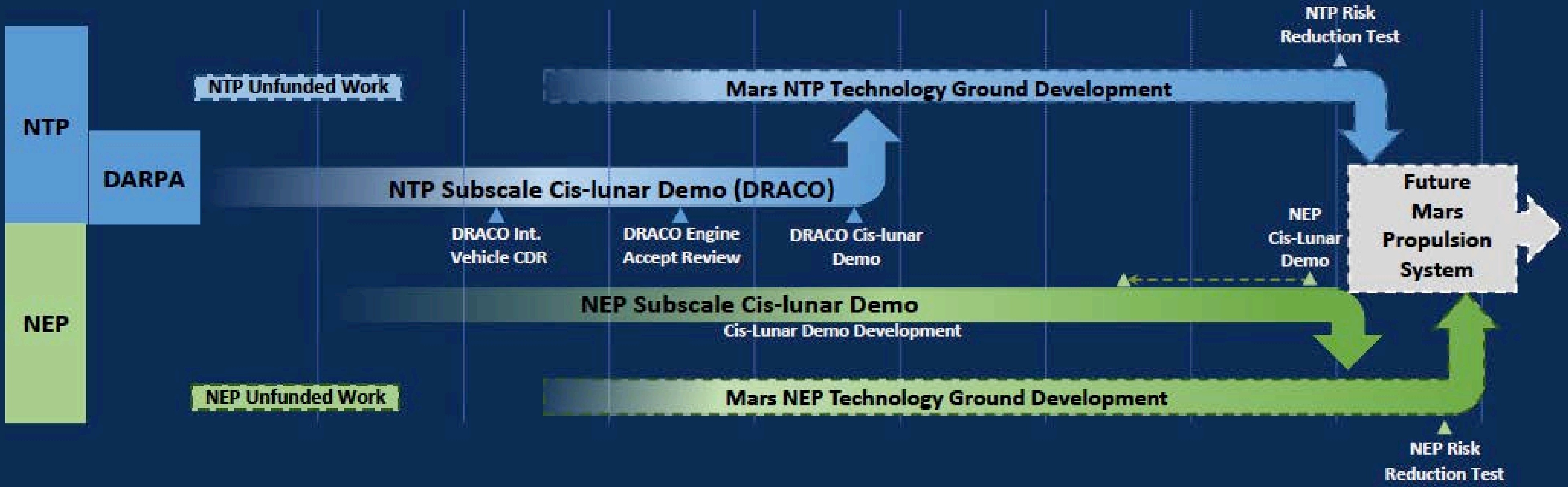
Pursuant to FY 2023 Enacted Appropriation (117-328)/Nuclear Thermal Propulsion:

- NASA is encouraged to develop innovative nuclear technologies that enable a regular cadence of extended duration robotic missions to the lunar surface and Mars
- Not later than 180 days after the date of the enactment of this Act, the National Aeronautics and Space Administration shall provide a plan for the design of a flight demonstration

FY 2022 CHIPS Act; Public Law 117-767:

- USE IN ROBOTIC AND HUMAN EXPLORATION ACTIVITIES. The Administrator, in collaboration with other relevant Federal agencies and with industry, shall take all necessary steps to carry out research and development, ground-based testing and in-space testing, and other associated activities to enable the use of space nuclear propulsion in Administration robotic and human exploration activities, including in cargo missions to Mars in the late 2020's and crewed missions to Mars in the 2030's.
- (2) SPACE NUCLEAR PROPULSION PROGRAM. (A) In general. The Administrator shall establish a space nuclear propulsion program to carry out the activities described in paragraph (1). The Administrator shall submit to Congress a plan to achieve an in-space flight test of a nuclear propulsion system that could support the first crewed mission to Mars.

Space Nuclear Propulsion Roadmap



Nuclear Thermal Propulsion (NTP)

Objectives

- Demonstrate performance of an integrated NTP system in cis-lunar space to assess extensibility to a Mars mission
- Identify high value subsystem technologies that need further maturation to support a Mars mission
- Strengthen U.S. leadership in space through engagement with industry and other government partners

Current Status

- Fuels, materials and fabrication methods have matured to make a 900 sec Isp engine feasible
- Advanced design concepts for an integrated engine funded through industry engagements
- DARPA Demonstration Rocket for Agile Cislunar Operations (DRACO) partnership agreement targets a flight demonstration as early as FY 2027

Intended Infusion

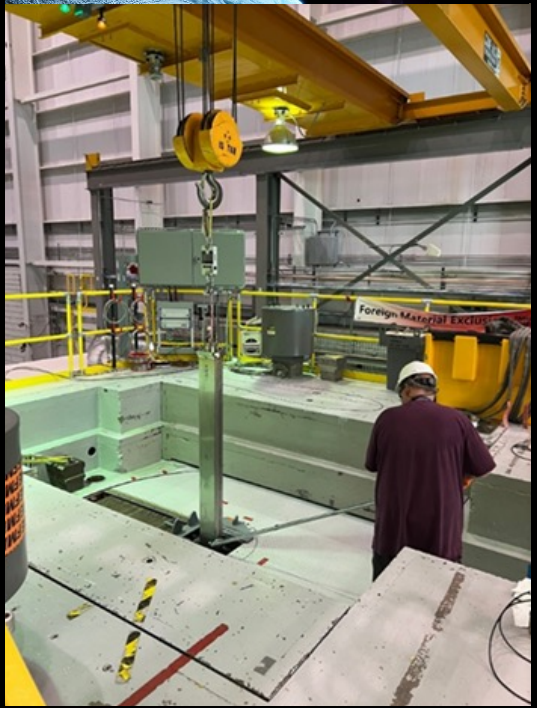
- Commercial cislunar transportation infrastructure
- Evolving M2M and deep space transportation

External Participation

- BWX Technologies, Department of Energy (DOE), DOE Idaho National Laboratory, DOE Los Alamos National Lab, GA, Ultra Safe Nuclear Corporation, Oak Ridge National Lab, MIT, DARPA, Lockheed Martin, Blue Origin, USSF

Deliverables/Schedule*

- FY 2024: DRACO System Preliminary Design Review and NTR Engine Critical Design Review



Nuclear Electric Propulsion (NEP)

Objectives

- Develop and demonstrate NEP integrated system at the subscale to identify subsystem gaps
- Balance NEP technology needs with relevant FSP system investments
- Maximize opportunities to leverage investments of other government agencies and stakeholders

Current Status

- Completed NEP Technology Maturation Plan for high power development – under final internal review
- Investments started for power and thrusters
- Cooperating with USSF on Joint Energy Technology Supplying On-Orbit Nuclear Power NEP project

Intended Infusion

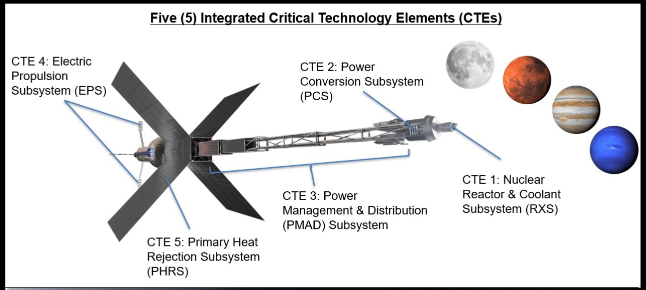
- NASA science missions, Department of Defense

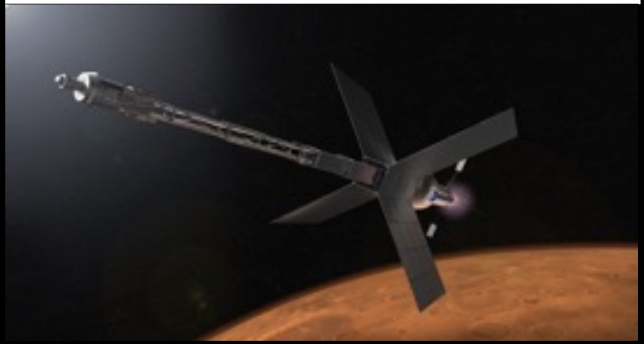
External Participation

- Department of Energy and Department of Defense

Deliverables/Schedule*

- FY 2025: Concept Design for NEP demonstration stage (10 kWe) critical technology elements designs
- FY 2026: System Requirements Review





DRACO Flight Demo Background

DRACO program is a partnership between NASA and DARPA to design, build, launch, and demonstrate the nation's first in-space Nuclear Thermal Rocket Engine (NTRE)

- NASA partnered on DRACO during Phase 2 before provider contract was signed
- NASA participated during proposal evaluation, award, and contract negotiations
- NASA has worked with all potential NTRE reactor developers under the SNP project

Joint roles and responsibilities provided by an Interagency Agreement (IAA) signed in January 2023

- NASA is responsible for oversight of industry's design, fabrication, testing, and delivery of the NTRE
- DARPA is responsible the mission, concept of operations, and all safety and regulatory compliance including launch authorization

DRACO industry contract with equal cost sharing between NASA and DARPA

US Space Force procuring the Vulcan/Centaur for March 2027 Launch as part of FY24 two-year task order

NASA Governance Approach

Context

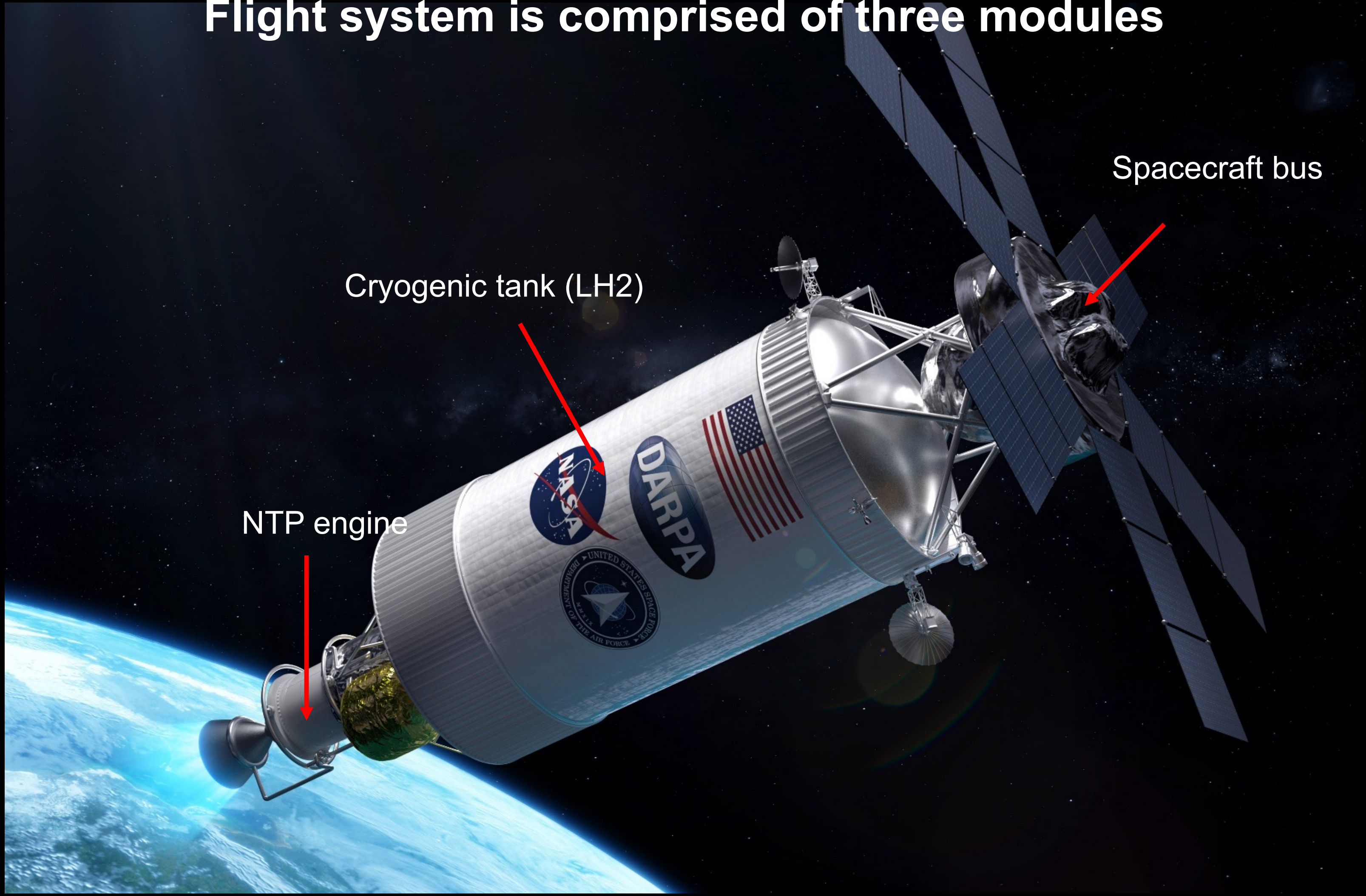
- DARPA owns and controls the performer's contract and NASA cannot unilaterally enforce compliance to NASA standard program management practice
- DARPA prioritizes schedule, cost and flexibility against risk aversion and NASA must adapt using lean and agile management approach that significantly reduces programmatic overhead
- DRACO is an experimental demonstration that inherently carries technical uncertainty related to a fully successful flight

Process

- NASA will allow for a C/D equivalent mission risk class for protection of personnel or other high-value assets, nor is execution of any other project dependent on its success
- NASA has adopted a joint-management structure that pushes technical decisions to the engineering teams while maintaining appropriate independent assessment review and technical authority control lines
- NASA will implement a tailored set of reduced program management measures that takes advantage of a highly integrated NASA, DARPA, and performer teams using embedded subject matter experts for real-time

DRACO Vehicle System Overview

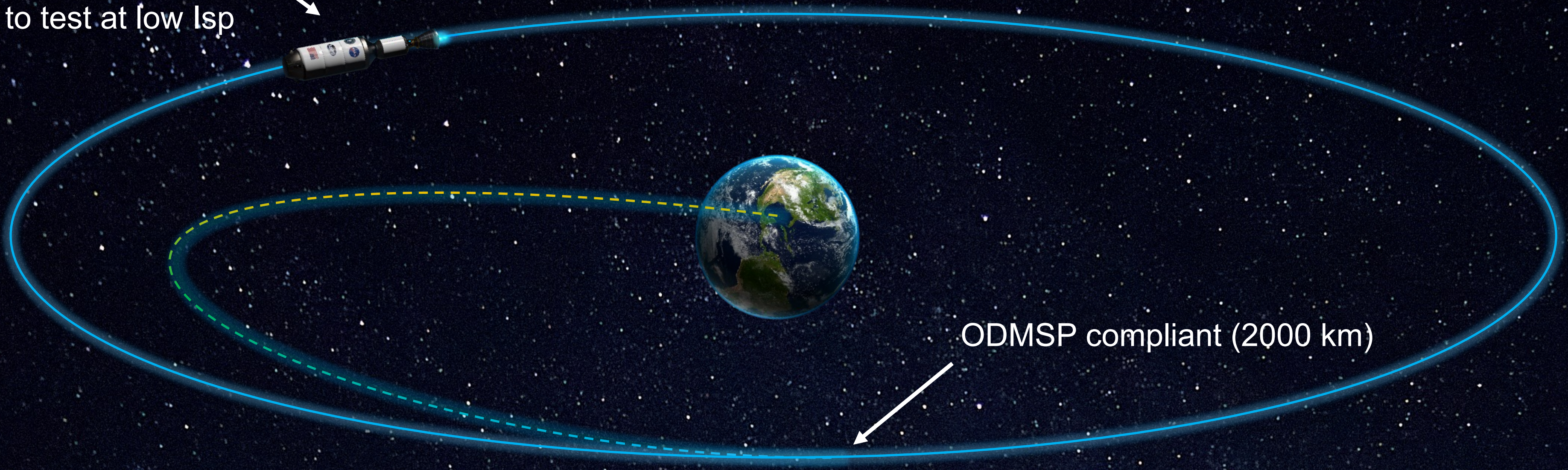
Flight system is comprised of three modules



DRACO Architecture Overview

DRACO Vehicle
- Low thrust for demo (preserves LH2)
- Capable of high Isp but allowed to test at low Isp

Nuclear Launch Safety
- DRACO vehicle is the launch vehicle payload
- Reactor includes inhibits to prevent turning on reactor
- Reactor activated after successful orbit insertion



Objective of mission is to collect data on novel HALEU NTR behavior

Engine Extensibility

DRACO Flight Demonstrator

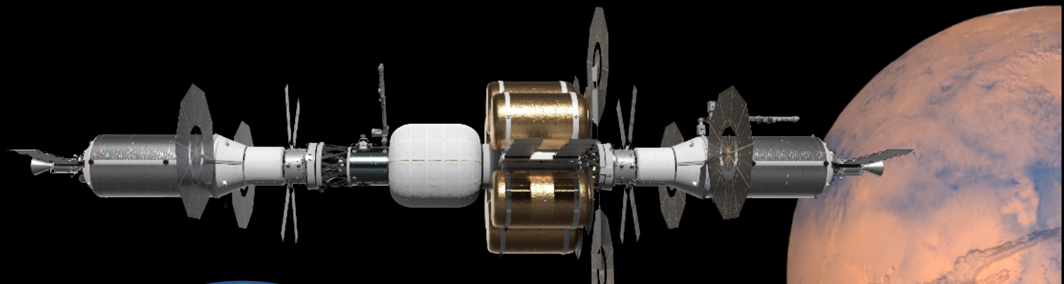
High Assay Low Enriched Uranium (HALEU) fuel

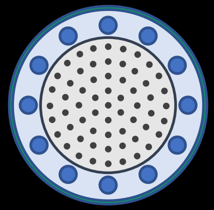
Modular core design scalable to higher thrust for Mars

Reactor core operating temperature >2700K

4+ hour engine life with repeatable starts and stops

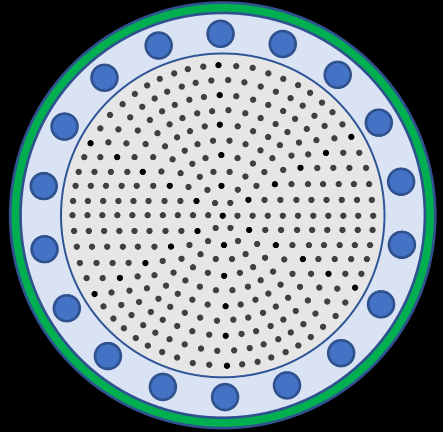
Mission duration limited by cryogenic propellent supply



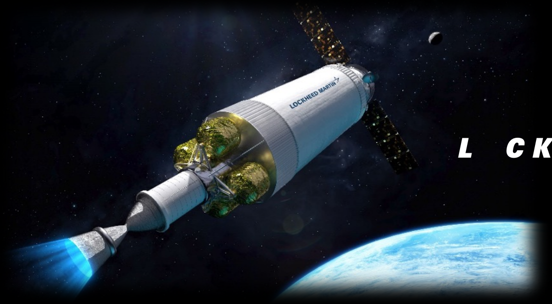


Extensibility

- Core power & size increases by adding fuel elements; fuel element & moderator block design remains the same
- Increase number of control drums; control drum design remains the same



Demonstration Reactor



Mars Mission Reactor

Human Lunar Lander/Mars Transportation Study (2023)

Fuel: High Assay Low Enriched Uranium (HALEU)

Thrust per engine: 15000-25000 lbf

Chamber Temperature: 2700-2800K

Engine Life: 4 hrs at rated thrust performance

Cryo Management: Active, Near-Zero Boiloff

NASA NTRE Project Team

- **Assembled a team of subject matter experts to provide technical oversight and insight during the DRACO Nuclear Thermal Rocket Engine (NTRE) design and assembly stage**
- **Focus is to provide early tracking for critical risks, facilitate development of the NTRE, while establishing the knowledge path needed to establish an operational system**
- **Insight support**
  - Offer feedback to DRACO prime and subprime organizations on potential design/assembly challenges during formal design reviews (SRR, PDR, CDR, etc.)
  - SME attendance at weekly contractor working meetings for effective and timely communication
  - Provide independent evaluation, technical knowledge, and lessons learned using previous NASA program experience
- **Tool Development**
  - Refine existing analysis methods and develop of new models tailored to nuclear rocket engines
- **Current Status**
  - Basic reactor core design and fission fuel recently fixed and future design changes limited to evolutionary modifications
  - Three ‘reactor’ builds: EDU (manufacturing, integration and assembly, cold flow testing); proto-flight unit (full assembly, vibration testing, and thermal-vacuum testing); flight unit
  - NEPA and launch authorization process are fully engaged. NEPA draft published in October, received no public comment (NASA is a Cooperating Agency on NEPA)

Benefits of DARPA Partnership

Enables technical progress and results in accumulating success and pathfinding capabilities for future missions

Mission Success Criteria

- **Threshold:** Development and safe launch of the demonstration vehicle
- **Goal:** Reactor start and operation on orbit (thrust) of Nuclear Thermal Rocket Engine (NTRE)

Benefits to NASA

- Provides alignment with current Congressional direction to advance NTP capability
- Exercises the design, build, and test of an integrated NTRE system
- Acquires relevant functional data during all phases
- Establishes performance data that will be used to inform future developments
- Establishes an interagency regulatory basis for launching and operating a space nuclear system
- Identifies the technology gaps to be addressed for future operational flight systems
- Leverages OGA shared funding investment to demonstrate NASA technology advancements

Summary

- NASA is actively engaged with internal and external agency groups to cooperatively establish common practices, procedures, and roadmaps for space nuclear technologies
- NASA continues to closely engage commercial capabilities and innovations to advance small, low mass HALEU reactor solutions
- DRACO flight demonstration aligns with Congressional directions (FY23 enacted appropriation 117-328 on nuclear thermal propulsion and Public Law 117-767 on nuclear propulsion system)
- DRACO partnership offers an extensive cost sharing opportunity for NASA and DOD that allows for a nearer term flight demonstration of a Nuclear Thermal Rocket Engine and advance early technology maturation for nuclear propulsion