EXPLORE SPACE TECH
TECHNOLOGY DRIVES EXPLORATION

GO: Space Nuclear Propulsion
NASA Space Technology Mission Directorate

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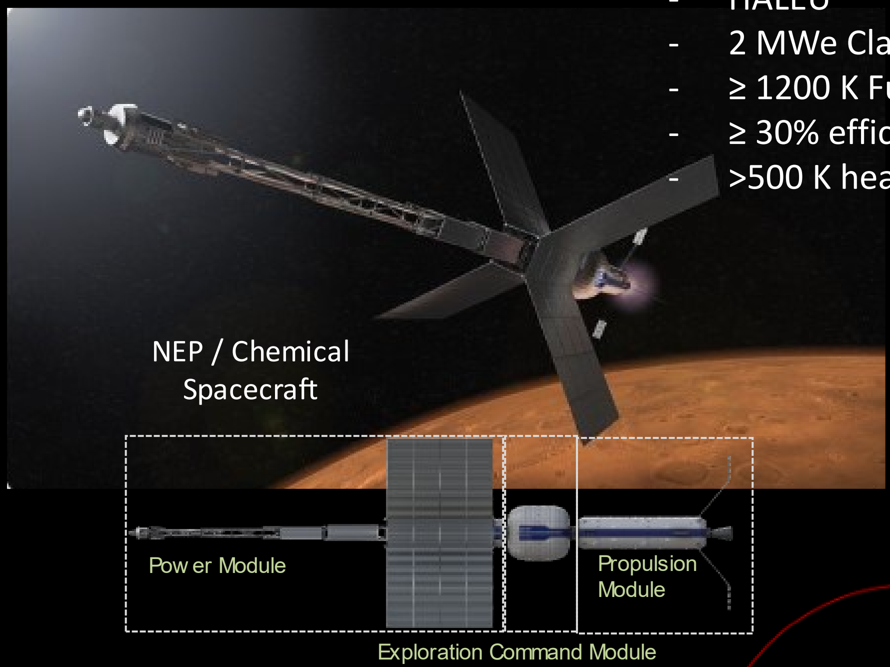
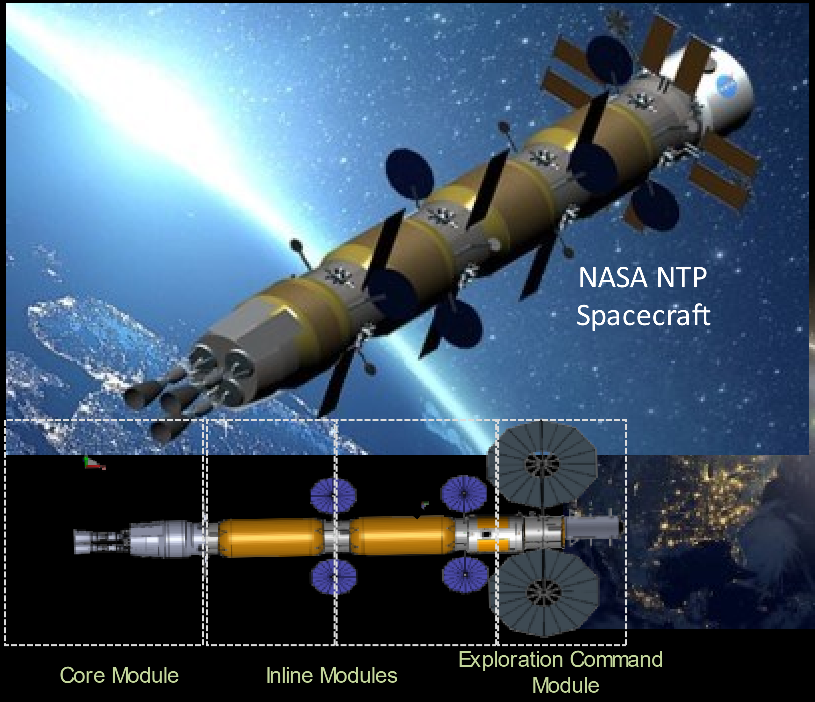
GO: Develop nuclear technologies enabling fast in-space transits.

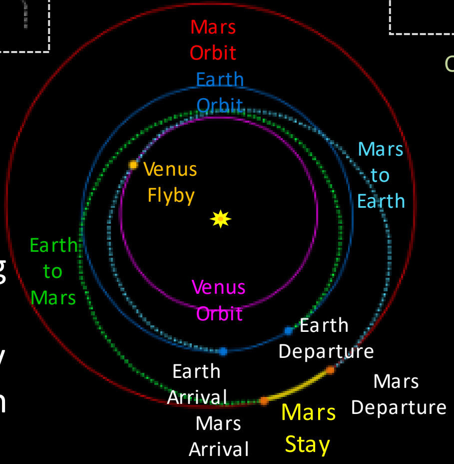
Initial Parallel Path for Nuclear Thermal Propulsion and Nuclear Electric Propulsion Technologies for future Cis-Lunar, Mars and Deep Space Exploration Missions.

- HALEU
- 2 MWe Class
- ≥ 1200 K Fuel
- ≥ 30% efficient Brayton
- >500 K heat rejection



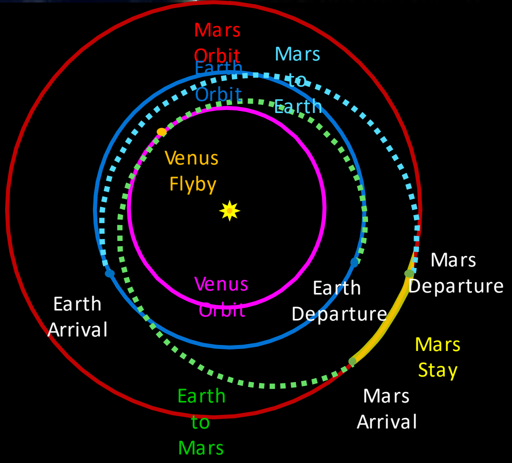


- HALEU
- > 2700 K Fuel to support
  > 900 s I_{SP}



- High Δ-velocity orbit maneuvering
- Strategic placement of space platforms
- Cis-lunar and Mars transportation staging
- Asteroid rendezvous and sample return
- Robotic and piloted deep space planetary missions including <750 day (TBR) Human Mars round trip
- MWe Class Nuclear Electric Propulsion

- Cis-lunar and Mars transportation including <750 day (TBR) Human Mars round trip
- Synergy with Department of Defense cis-lunar operations
- High thrust stage for fast outer planet, robotic science missions

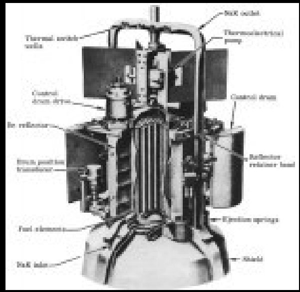


All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

GO: Develop nuclear technologies enabling fast in-space transits: State of the Art

Space Heritage (TRL 9)

500 We Space Fission Reactor
4.5 kW Hall Effect Thruster Strings
25 kWe Space Station Freedom Brayton
70 kWt, 35 kWt per loop ISS System
290 K Radiators



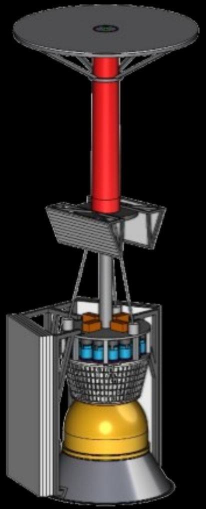
500 W_e, 1965

4.5 kW Hall Thruster

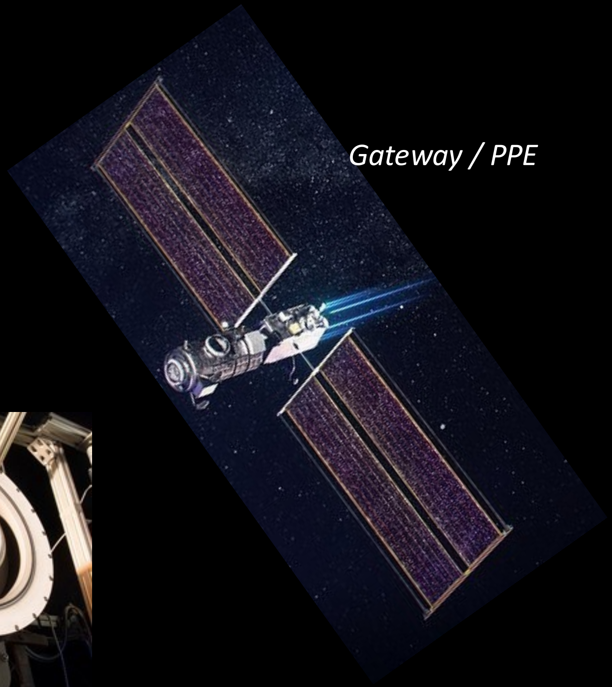
Radiators / Cooling Loop

Space Technology In Development

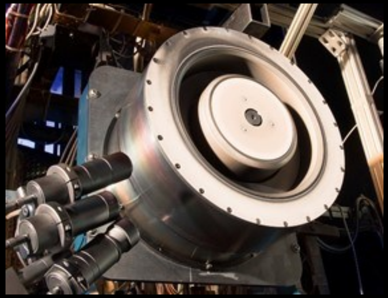
12.5 kW Hall Effect Thruster Strings – TRL 6
50 kW Solar Electric Propulsion System – PPE – TRL 5
Fission Surface Power – TRL 4 for 1 kWe, TRL 3 for 10 kWe
Design contracts released
HALEU Fuel Development:
- TRL 2 for > 2700 K fuel
- TRL 5 for < 2500 K fuel
1.1 GW Rover/NERVA engine – TRL 6
Subscale engine – reactor contracts – TRL 3
DARPA DRACO NTP Demonstration



Fission Surface Power



Gateway / PPE



12.5kW Hall Thruster

DRACO

Terrestrial

Non-radiative cooled
Non-space environment

Nuclear Propulsion Roadmap Summary

Nuclear Electric Propulsion

- **Phase 1: Requirements Definition**
  - Define system requirements (e.g. system kg/kW threshold), identify industry opportunities with a make buy decision
- **Phase 2: Reactor Fuel & Moderator Development and Subsystem technology Maturation**
  - Industry and Government technology maturation efforts in parallel (Brayton, Radiators, PMAD, Thruster, etc.)
  - Reduce level of uncertainty on technical effort, program cost, and program schedule for an integrated system
  - DOE focus on fuel and moderated reactor design options

Nuclear Thermal Propulsion

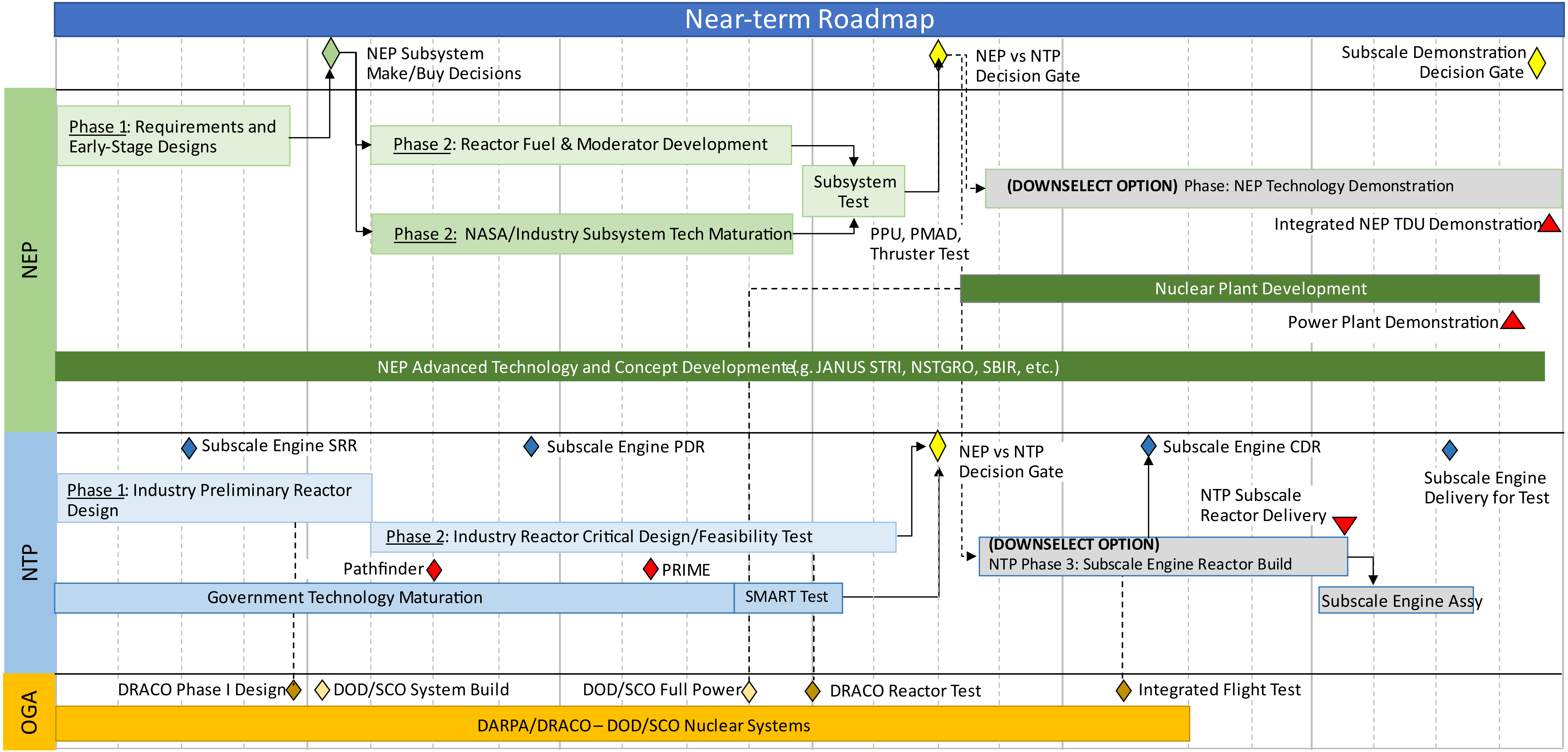
- **Phase 1: Industry Preliminary Reactor Design**
  - Preliminary reactor design industry efforts and high-temperature reactor fuel and materials development (Selected 7/21)
- **Phase 2: Industry Reactor Critical Design/Feasibility Test**
  - Critical reactor design and proof of concept tests from industry
  - Government PRIME test demonstration of reactor fuel and material maturity
  - Government SMART test of a fuel element in subscale reactor

NEP vs NTP Decision Point

- **OPTION: Phase 3: NEP Technology Demonstration**
  - Stepwise assembly of government and industry subsystems for a non-nuclear, integrated NEP TDU test
  - Independent Nuclear Power Plant Development

- **OPTION: Phase 3: NTP Subscale Engine Test**
  - Build subscale reactor and assemble subscale engine for a ground demonstration test

Nuclear Propulsion: Near-term Roadmap



Notional Timeline

Phase 1: Early Technology and Design Development Requirements

Nuclear Electric Propulsion

- Human Mars Architecture studies provide a reference point of departure.
  - Further engineering needed to define performance requirements, subsystem designs and qualification approaches
  - Incorporate industry and academic information gained through multiple technical interchange meetings held during FY21

Objectives / Deliverables:

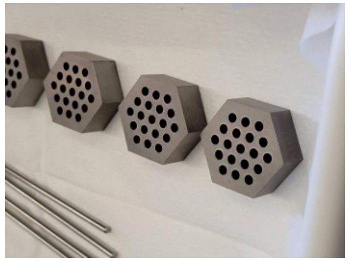
- Establish Level 1 (mission) and Level 2 (system) requirements
- Develop a government reference design
  - Develop detailed subsystem designs (industry and in-house); level 3 requirements (Design to Schedule): system design trades, interface definition, component designs
  - Reactor design (fuel and moderator) and primary heat transport
  - Power Conversion and PMAD
  - Heat rejection and thermal radiators
  - Electric propulsion (Thruster, PPU and Flow Control)
- Complete Make / Buy decision analyses
- Define Phase 2 priorities and risk assessment
- Identify rapid development investments for advanced propulsion concepts with defined proof-of-feasibility tests

Nuclear Thermal Propulsion

- Continue to advance the HALEU fuel and reactor materials development with DOE to support >2700 K reactor temperature
  - Establish industry preliminary reactor designs solutions for a subscale engine (Selected 7/21)
  - Determine design and testing options for various engine components and development activities

Objectives/Deliverables

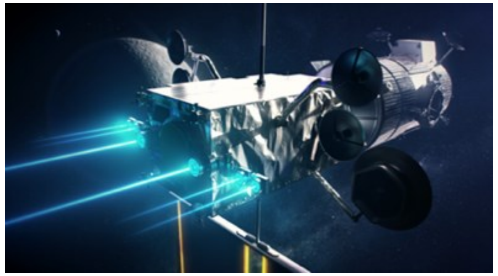
- Execute reactor preliminary design contracts with industry
- Subscale reactor and non-nuclear engine component PDR design
- Complete INL TREAT reactor modifications for PRIME reactor fuel and materials demonstration test.
- Define objectives, and design requirements for the SMART subsystem reactor test
- Develop requirements, determine location, and begin detailed engineering of a subscale ground demo facility.
- Begin build up of Hardware-in-the-loop software testing facility



Phase 2: Engineering Component and Subsystems Maturation

Nuclear Electric Propulsion

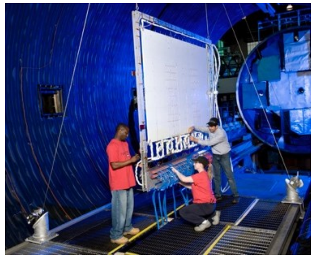
- Parallel investments from Industry and Government for multiple subsystem alternatives
- Leverage on-going NASA efforts on EP, FSP, and Electrified Aircraft
- Partner with DOE/DOD to adapt terrestrial reactor and power system technologies



Objectives:

- Assess current facility capabilities and required upgrades
- Perform risk reduction testing to evaluate materials and environments
- Develop subsystem prototypes for testing and analysis
- Down select advanced concepts with high potential for mid-TRL advancement and prototype demonstration

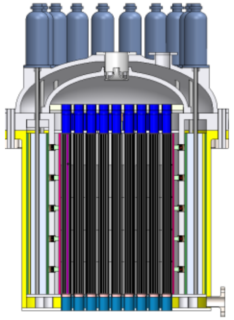
Deliverables:

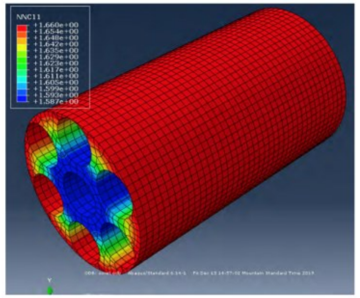


- Facility requirements and/or upgrades
- Reactor materials test results and recommendations
- Power conversion design and test plan
- Sub-scale radiator TVAC test with heat transfer loop
- Transformer demonstration, prototype high-voltage system model
- Prototype EP thruster testing
- DDU/PPU design and IEEE parts assessment

Nuclear Thermal Propulsion

- Completion of subscale engine design
- Begin work on software integration laboratory systems testing with hardware in the loop
- Begin development of subscale ground demo test facility and SMART reactor
- **Objectives/Deliverables**
- Execute industry reactor CDR designs and proof of concept test
- PRIME reactor fuel and materials demonstration test results
- SMART reactor licensing, environmental impact statement, and detailed engineering
- Engine component CDRs, Subscale engine CDR and DCR
- Preliminary design work for ground testing stand and scrubber system; facility licensing and environmental impact statement
- Non-nuclear component risk reduction tests





Moderator Block Reactor Core

Phase 3: Technology Capability Demonstration

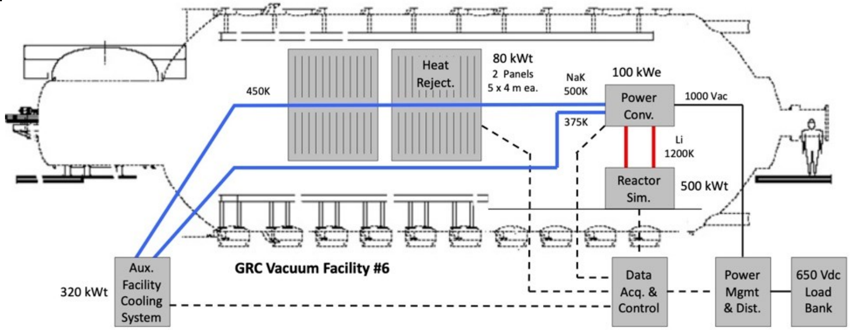
Nuclear Electric Propulsion

Objectives:

- Non-nuclear integrated TDU Test of major power subsystems at representative scale in relevant environment (To achieve TRL 5)
- Nuclear Testing of NEP fuel and moderator segments at operating temperature fluence & burnup
- Identify and prep nuclear reactor ground test facility
- High Power Propulsion Demonstration

Deliverables:

- High-fidelity reactor design and validation test plan
- Fabrication and acceptance testing of power subsystems at contractor facilities
- Delivery and integration of EP subsystems at NASA facility; Initial performance and erosion testing
- PMAD and DDU parts characterization and testing (temperature, voltage, and radiation)



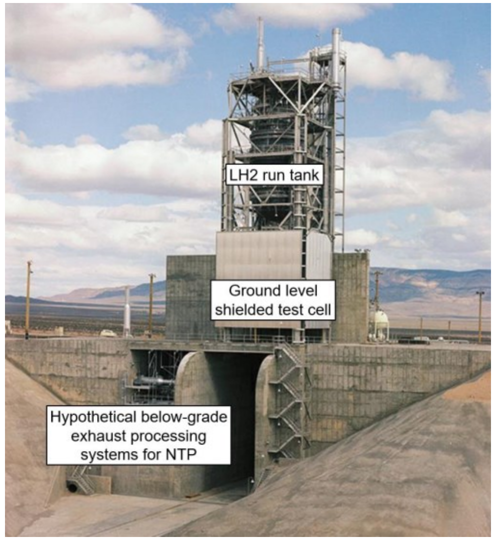
Nuclear Thermal Propulsion

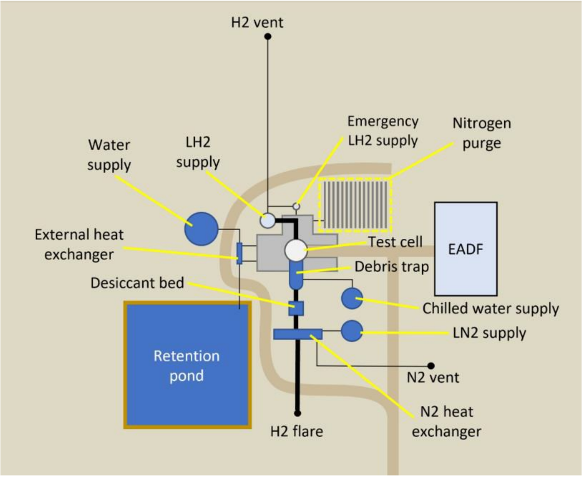
Objectives:

- Complete integration of non-nuclear turbomachinery, nozzle, and nuclear reactor into a full subscale system
- Perform integrated subscale engine demonstration and verify system performance capability including > 900 second I_{SP}

Deliverables:

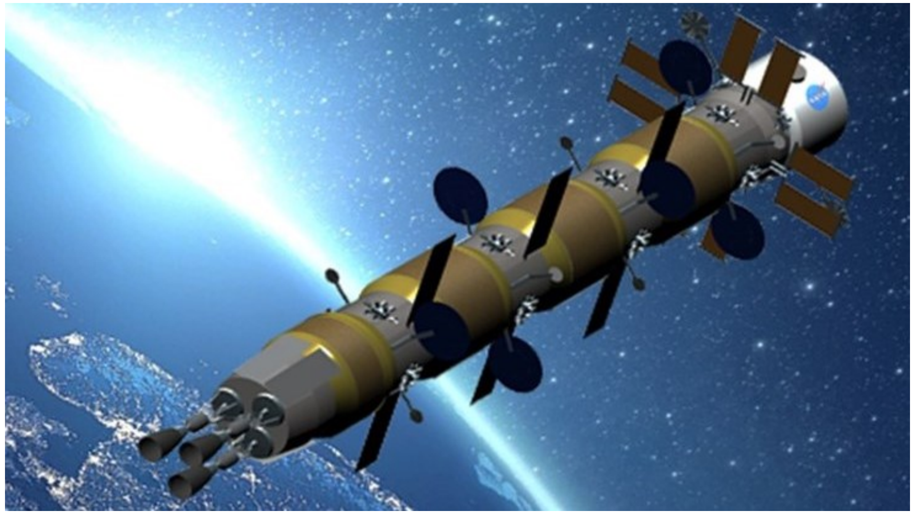
- Complete reactor design specification and documentation
- Subscale engine performance capability and preliminary operational envelope
- Proof of design concept for a fully integrated NTP engine
- Ground demonstration of a subscale integrated system



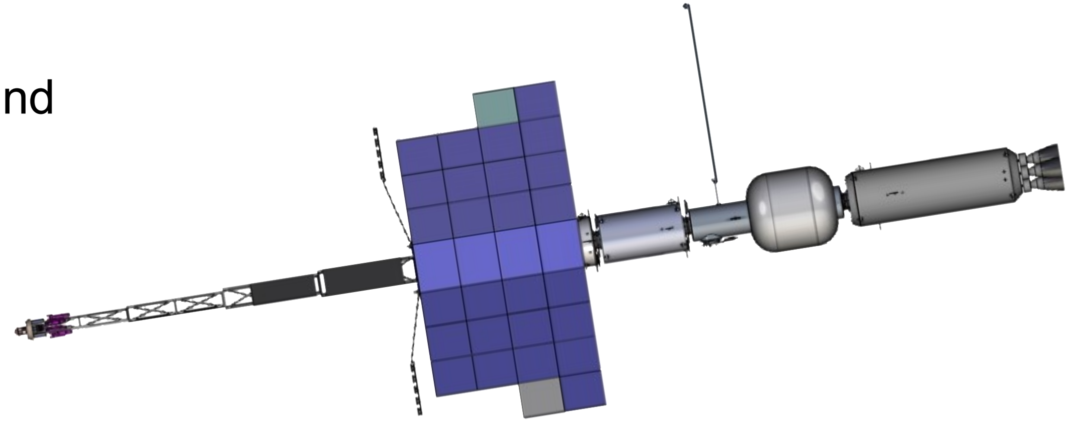


Phase 4: Mission Relevant Flight Demonstration

Flight Demonstration (Notional)



- Flight demonstration of nuclear propulsion capability
- Leverage of Department of Energy partnerships as appropriate
- Either NEP or NTP would be a fully integrated, mission relevant system
- Potential mission opportunity could include Mars EDL technology demonstration mission
- An NTP capability demonstration has potential partnership with DOD
  - Stakeholder / informed by DARPA DRACO partnership / products
- Demonstrate compliance with nuclear testing transportation and/or launch regulatory requirements
- Demonstrate active cooling through coordination with CFM and achieve CFM flight system test objectives



Capability Gap Priorities / Next Steps

Nuclear Electric Propulsion

Near-term

- HALEU Fueled 2 MWe Class Space Reactor Design ≥ 1200 K
- High voltage power system
- 2 MWe Class Propulsion system string prototype
  - Parallel / Leader follower approach w/ multiple thruster options
  - Steady State Thermal and ≥ 100 hrs
- Develop detailed subsystem designs (industry and in-house)
- IEEE Parts Topology Assessment

Mid-term

- ≥ 1200 K Fission Power Reactor, up to 10 MWt
- Brayton Power Demonstration ≥ 30% efficiency, up to 500 kW per unit
- Pumped Loop Heat Rejection, 1.5 MWt per loop, > 500 K
- 5 MW Class High temperature (> 500 K) radiator
  - ≤ 3 kg/m^2, < 1 kg/kW

Gap Closure

- NEP Integrated Pathfinder Flight Demonstration

Nuclear Thermal Propulsion

Near-term

- HALEU Fuel > 2700 K (2700 K Hydrogen) to support I_{SP} > 900 s
- Comparable reactor structural materials / hydrogen compatible
- 3 contractors selected for reactor PDR
  - Anticipating 2 contractors to proceed to CDR under Phase 2
- Prototypic Reactor Irradiation for Multicomponent Evaluation (PRIME) Test: CerCer fuel and insulated moderator in flowing hydrogen
- Design SMART and subscale ground test facility
- Subscale Maturation of Advanced Reactor Technologies (SMART) Test: Multiple NTP fuel and moderator elements into a driver core system.
  - Raise NTP material up to criticality with hydrogen flow testing

Mid-term

- 12.5 klbf non-nuclear engine (controls, cold flow, power pack)
- Ground Support & Ground Test Infrastructure Required for subscale ground demonstration and SMART
- Empirically Anchored Models & Simulation Capabilities Supporting NTP Engine System Design and Digital Twin Systems Engineering
- Begin development of long lead items required for full scale NTP certification ground test facility

Gap Closure

- NTP Integrated Pathfinder Flight Demonstration
  - Potentially w/ integrated CFM

Acronyms and Abbreviations

- ΔV : Delta-V; Change in Velocity
- Assy: Assembly
- CerCer: Ceramic-ceramic
- CDR: Critical Design Review
- DARPA: Defense Advanced Research Projects Agency
- DCR: Design Certification Review
- DDU: Data Display Unit
- DOD: Department of Defense
- DOE: Department of Energy
- DRACO: Demonstration Rocket for Agile Cis-lunar Operations
- EDL: Entry, Descent, and Landing
- EP: Electric Propulsion
- FSP: Fission Surface Power
- FY: Fiscal Year
- HALEU: High Assay Low Enriched Uranium
- IEEE: Institute of Electrical and Electronic Engineers
- INL: Idaho National Laboratory
- Isp: Specific impulse
- ISS: International Space Station
- NASA: National Aeronautics and Space Administration
- NEP: Nuclear Electric Propulsion
- NTP: Nuclear Thermal Propulsion
- OGA: Other Government Agencies
- PDR: Preliminary Design Review
- PMAD: Power Management and Distribution
- PPE: Power and Propulsion Element
- PPU: Power Processing Unit
- PRIME: Prototypic Reactor Irradiation for Multicomponent Evaluation
- SCO: Strategic Capabilities Office
- SMART: Subscale Maturation of Advanced Reactor Technologies
- SRR: System Readiness Review
- STMD: Space Technology Mission Directorate
- TBR: To Be Resolved
- TDU: Technology Demonstration Unit
- TREAT: Transient Reactor Test
- TRL: Technology Readiness Level
- TVAC: Thermal Vacuum