

NASA Envisioned Future Priorities for In-Space Transportation

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STMD Strategic Framework

Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Habitation System technologies.

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop technologies for science instrumentation supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries

Nuclear
TX 1.4.3 Nuclear Thermal Propulsion
TX 3.1.2 Heat Sources (Fission)
TX 3.1.4 Dynamic Energy Conversion
TX 3.3 PMAD

Power SCLT
TX 3.1.2 Heat Sources (Fission)
TX 3.1.4 Dynamic Energy Conversion
TX 3.3 PMAD

Propulsion PT
TX 01 Propulsion Systems

Thermal SCLT
TX 14.1 Cryogenic Systems
TX 14.2 Thermal Control Components and Systems
TX 14.3.1 Thermal Protection Materials

EDL SCLT
TX 9.2.2 SSRP
TX 9.3.2 Prop for Landing
TX 9.1.3 Sails / Booms
TX 9.4 Vehicle Systems

TX 13.1.1 Natural and Induced Env. Characterization and Mitigation
TX 13.1.4 Propellant Production, Storage and Transfer
TX 13.2 Test and Qualification
TX 13.2.2 Propulsion, Exhaust and Propellant Management
TX13.2.6 Advanced Life-Cycle Testing Techniques

ISRU SCLT
TX 3.1.2 Heat Sources

Autonomy SCLT
TX – Pervasive
(Sensing and perception, fault monitoring and response, behavior and intent prediction, operation assurance, etc.)

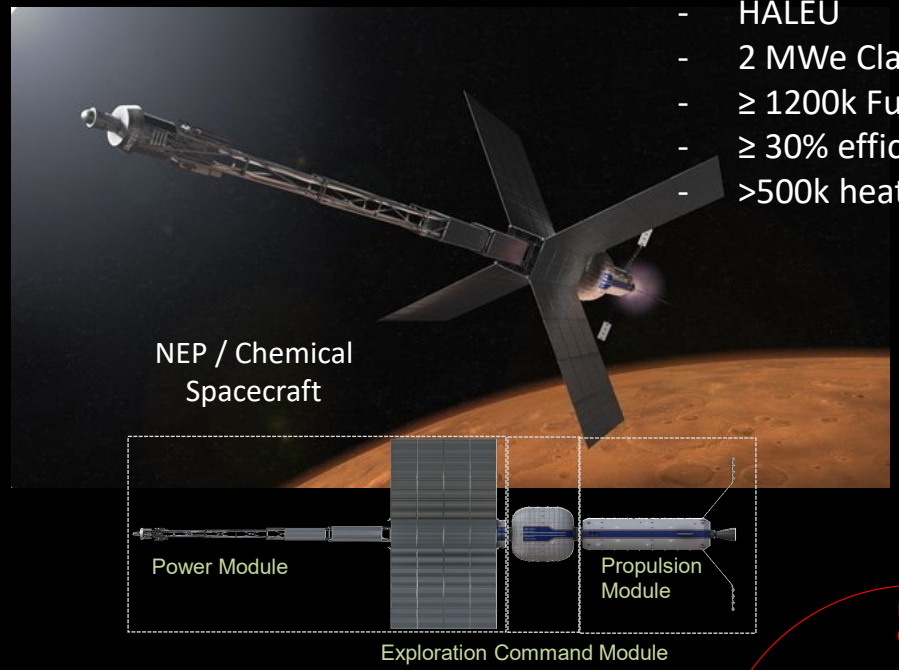
Rendezvous and Capture SCLT
Orbit Servicing / Propellant Transfer

Small Spacecraft CLT
TX 3.1.6 Advanced Concepts
TX 3.3 Power Management and Distribution
TX 2.1.1 Radiation-Hardened Extreme Environment Components

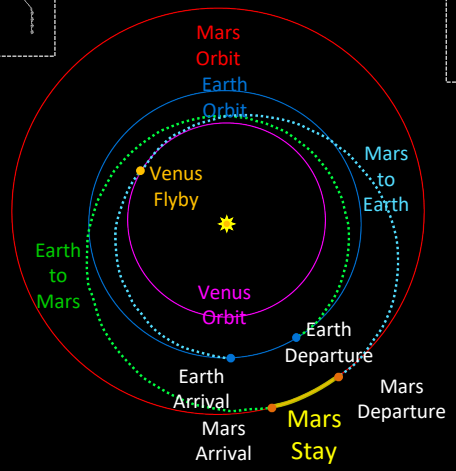

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION
GO - Space Nuclear Propulsion

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

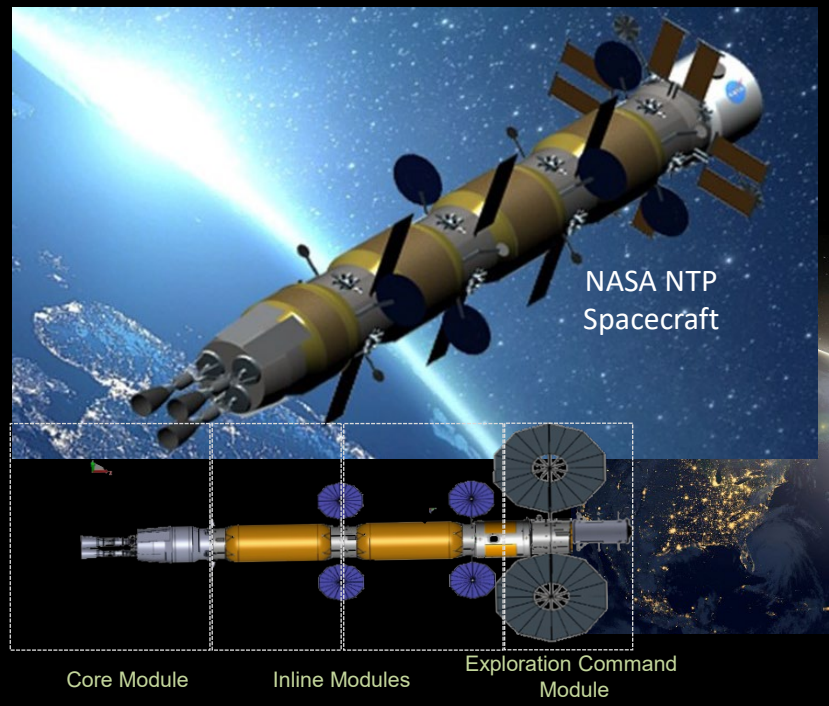
Initial Parallel Path for Nuclear Thermal Propulsion and Nuclear Electric Propulsion Technologies for Mars, Cis Lunar, and Deep Space Exploration Missions with down-select anticipated in CY25.



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



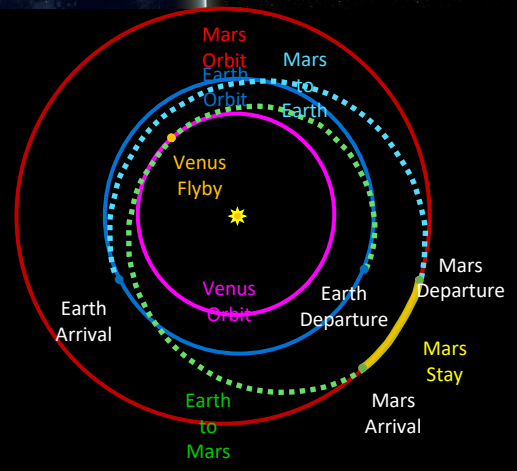
- High Δ-velocity orbit maneuvering
- Strategic placement of space platforms
- Cis-lunar and Mars transportation staging
- Asteroid rendezvous and sample return
- Robotic and piloted deep space planetary missions including <750 day (TBR) Human Mars round trip
- MWe Class Nuclear Electric Propulsion



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



- 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

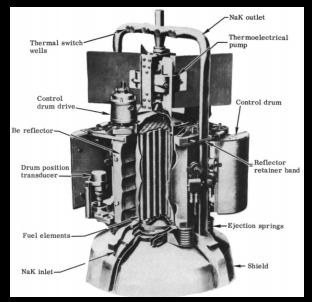


All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

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

Space Heritage (TRL 9)

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



500W$_e$, 1965



4.5kW Hall Thruster



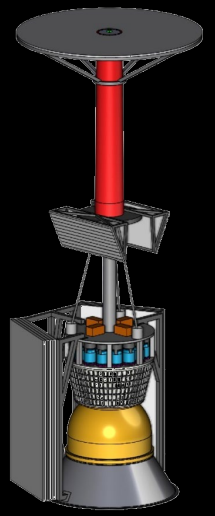
Radiators / Cooling Loop

Space Technology In Development

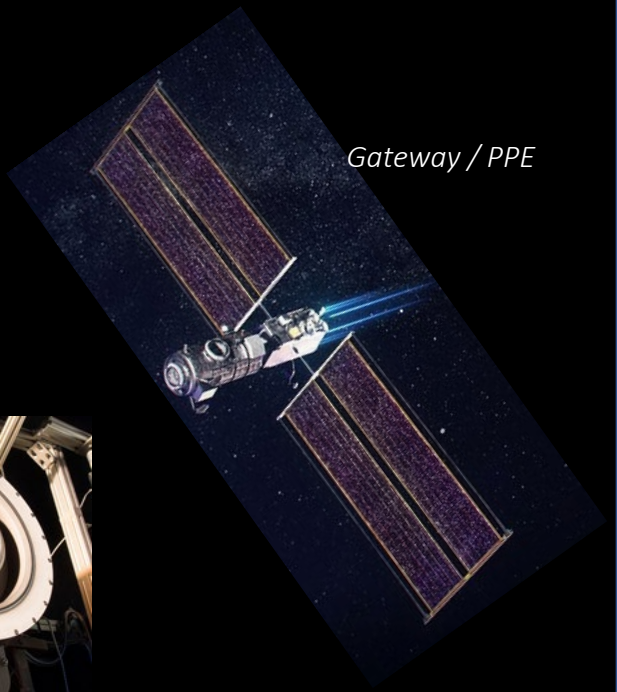
12.5kW Hall Effect Thruster Strings – TRL 6
50kW Solar Electric Propulsion System – PPE – TRL 5
Fission Surface Power – TRL 4 for 1kWe, TRL 3 for 10kWe
Design contracts released
HALEU Fuel Development:
- TRL 2 for >2700 K fuel
- TRL 5 for < 2500 k fuel
1.1GW Rover/NERVA engine – TRL 6
Subscale engine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



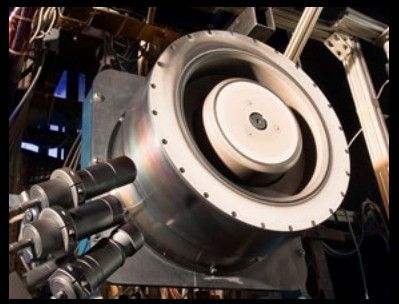
DRACO



Fission Surface Power



Gateway / PPE



12.5kW Hall Thruster

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

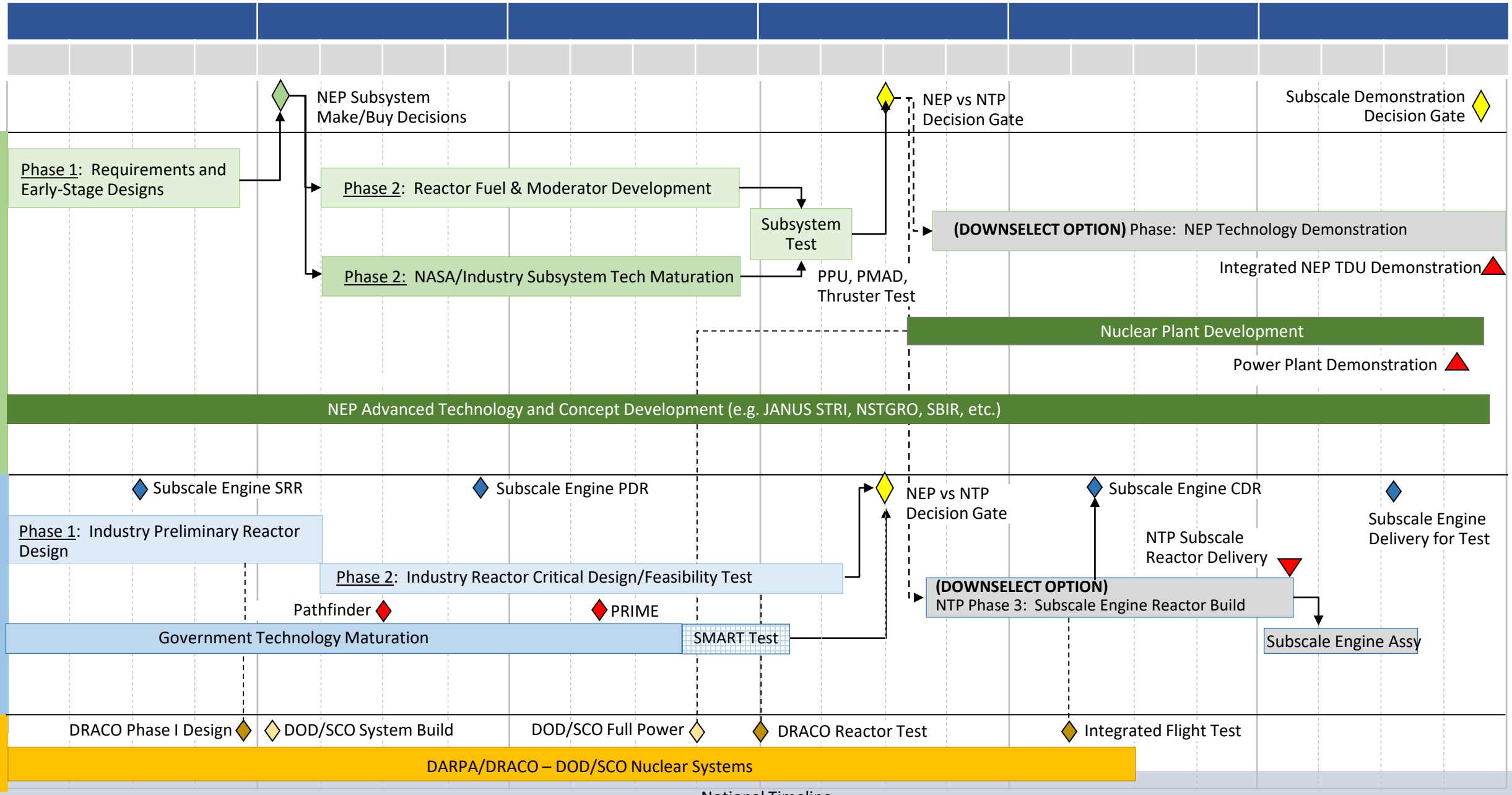
- **Phase 1: Industry Preliminary Reactor Design**
  - Preliminary reactor design industry efforts and high-temperature reactor fuel and materials development (Selected 7/21)
- **Phase 2: Industry Reactor Critical Design/Feasibility Test**
  - Critical reactor design and proof of concept tests from industry
  - 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



Phase 1: Early Technology and Design Development Requirements

Nuclear Electric Propulsion

- MTAS and the HEOMD 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

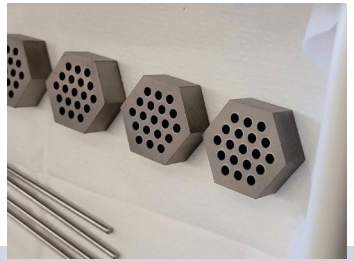


Nuclear Thermal Propulsion

- 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

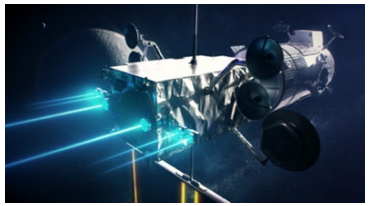
- Execute reactor preliminary design contracts with industry
- Subscale reactor and non-nuclear engine component PDR design
- Complete INL TREAT reactor modifications for PRIME reactor fuel and materials demonstration test.
- Define objectives, and design requirements for the SMART subsystem reactor 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

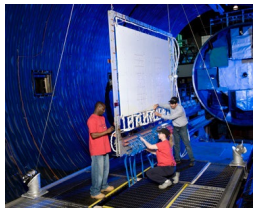
- Parallel investments from Industry and Government for multiple subsystem alternatives
- Leverage on-going NASA efforts on EP, FSP, and Electrified Aircraft
- Partner with DOE/DOD to adapt terrestrial reactor and power system technologies



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

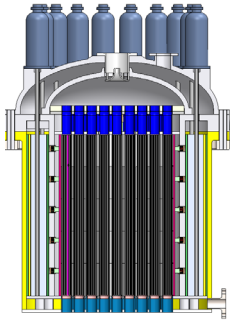
Deliverables:

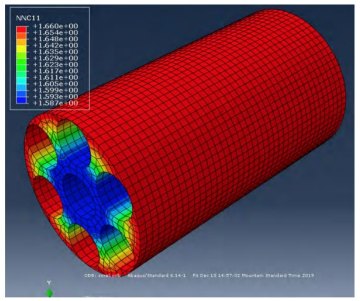


- Facility requirements and/or upgrades
- Reactor materials test results and recommendations
- Power conversion design and test plan
- Sub-scale radiator TVAC test with heat transfer loop
- Transformer demonstration, prototype high-voltage system model
- Prototype EP thruster testing
- DDU/PPU design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

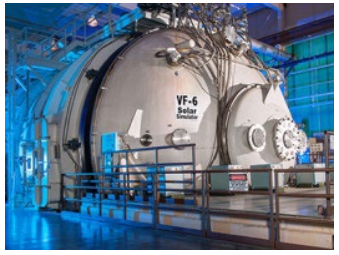
Objectives:

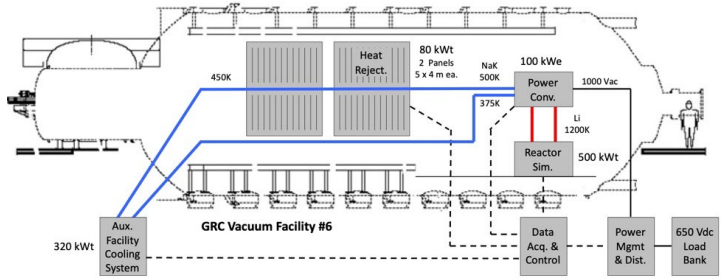
- Non-nuclear integrated TDU Test of major power subsystems at representative scale in relevant environment (To achieve TRL 5)
- Nuclear Testing of NEP fuel and moderator segments at operating temperature fluence & burnup
- Identify and prep nuclear reactor ground test facility
- High Power Propulsion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





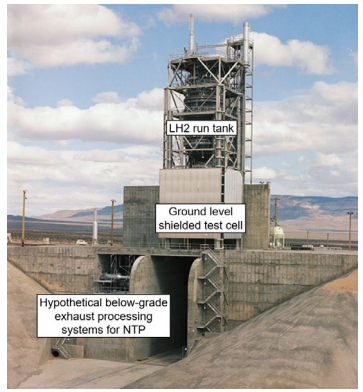
Nuclear Thermal Propulsion

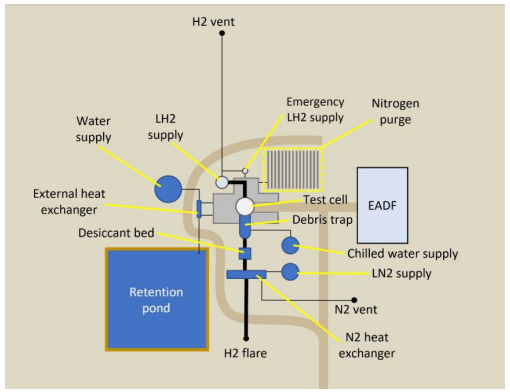
Objectives:

- 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

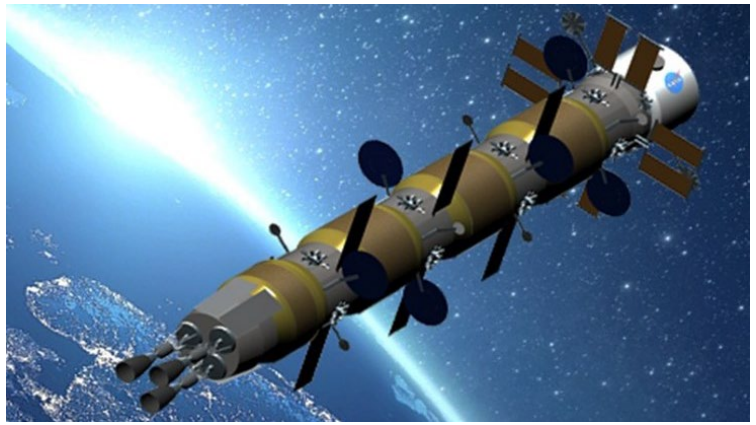


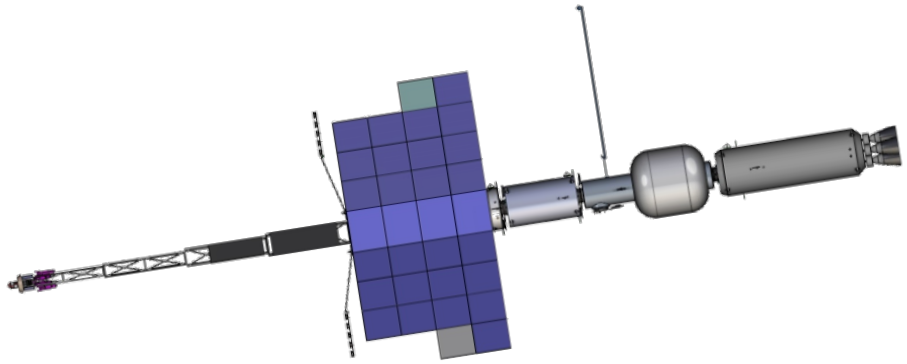


Phase 4: Mission Relevant Flight Demonstration

Early 2030's Flight Demonstration (Notional)

- Flight demonstrate of nuclear propulsion capability
- Either NEP or NTP would be a fully integrated, mission relevant system
- Potential mission opportunity could include STMD/HEOMD Mars EDL technology demonstration mission
- An NTP capability demonstration has potential partnership with DOD
- 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 2MWe Class Space Reactor Design ≥ 1200k
- 2MWe Class Propulsion system string prototype (Parallel approaches)
  - E.g. 100kWe Hall, VASIMR, MPD, etc. – Steady State Thermal and ≥ 100hrs
- Develop detailed subsystem designs (industry and in-house)
- IEEE Parts Topology Assessment

Mid-term

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

Gap Closure

- NEP Integrated Pathfinder Flight Demonstration

Nuclear Thermal Propulsion

Near-term

- HALEU Fuel > 2700k (2700k Hydrogen) to support I_{SP} > 900s
- 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

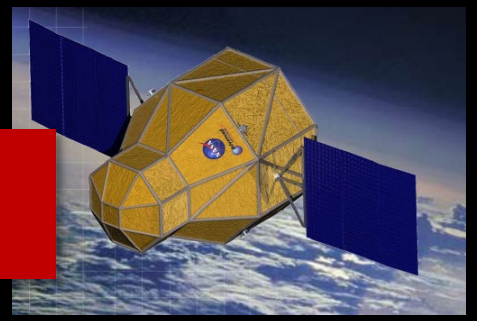
- NTP Integrated Pathfinder Flight Demonstration
  - Potentially w/ integrated CFM



GO - Cryogenic Fluid Management

GO: Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.

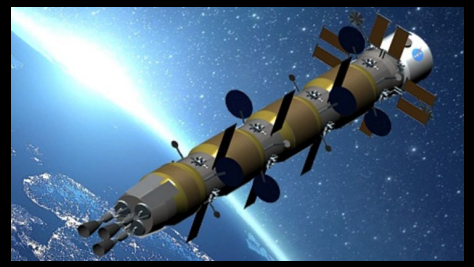
Developing technologies for near zero boil off storage, high efficiency chill-down and liquification, propellant transfer, and instrumentation to support Mars transportation and surface ISRU architectures.



STORAGE

- LOX, LCH4, LH2
- Near Zero Boil-off – Architecture / mission dependent

- **Critical Technologies**
  - Active Thermal Control
  - High Performance Insulation
  - Structural Heat Rejection/Intercept
  - Pressure Control
  - Operations
  - Near Zero Boil-off
  - Structural Multilayer Insulation
  - Low conductance structures
  - High Efficiency High Capacity 20k and 90k Cryocoolers
  - Destratification
  - Unsettled Mass Gauging
  - Thermal Control Coatings





LIQUEFACTION

- H2, O2, CH4
- Initial system performance:
  2 kg/hr of O2 and .3 kg/hr of H2
- Soft Vacuum insulation: 1.5 W/m2 at 250 K

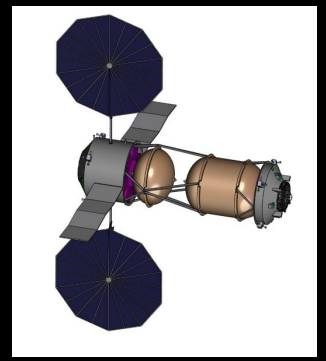




TRANSFER

- Propellant losses ≤1% during transfer
- <1% residual in supply tank

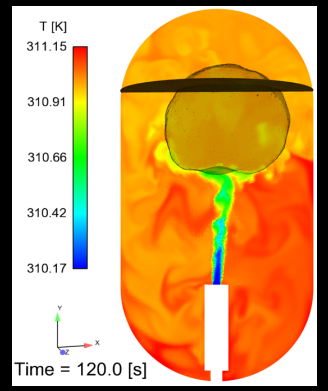
- **Critical Technologies**
  - Component Technologies
  - Operations
  - High efficiency chill down of tank and lines
  - Automated Cryo-Couplers
  - Low-leakage valves/actuators
  - Flow Meters
  - Efficient Liquid Acquisition Devices
  - Transfer pump



NON-PRIMARY PROPULSION

- Integrated RCS
- Fuel Cells
- ECLSS

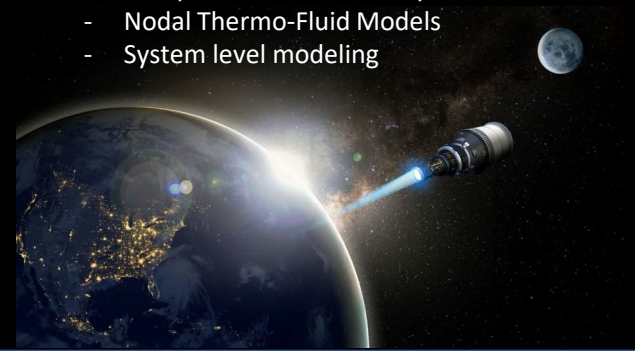
- Application Specific CFM Capabilities
- Uses components and processes from other categories



INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE

- Advanced instrumentation, data acquisition and signal processing
- Integrated Demonstration
- Accurate and robust a priori microgravity thermal-fluid predictions
  - Validated foundational physics in High Fidelity tools
  - High-to-Low Fidelity Model Integration

- Integrated System Performance Analysis
  - Low predictive uncertainty
  - Nodal Thermo-Fluid Models
  - System level modeling



CFM State of the Art

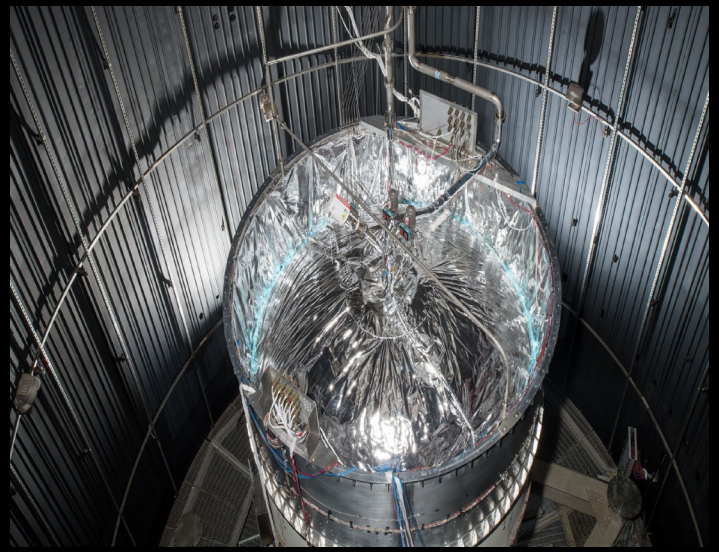
CFM capabilities must address the operational implementation and use of the technologies in a system, and the technical design of the CFM system. Many of the components required to close the gaps are the same but have diverging requirements or implementation strategies that change how the technology is used.

STORAGE

- Extensive experience in ground demonstration
- Longest H_2 cryogenic propulsion storage system has performed storage operations in space is 9 hrs
- Performed 4.5 Month CH4 subscale storage on RRM3

KEY Design Details

- Tank pressure regulation
- Methods of venting
- Structural heat load
- Total heat input over time
- Active cooling – **1W lift @ 20k; 20W lift @ 90k**



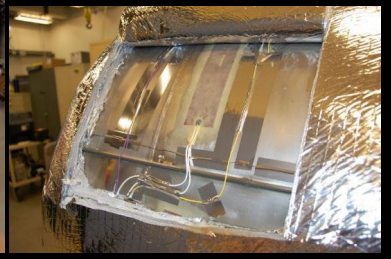
LIQUEFACTION

- **Ground based demonstration** and analytical performance model validation of **LN2**



KEY Design Details

- Condensation, fluid physics, fluid purity
- Active cooling integration
- High performance insulation in appropriate environment

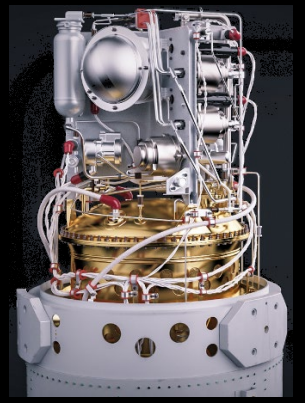


NON-PRIMARY PROPULSION

- **Ground based testing** of Integrated RCS in thermal vacuum

KEY Design Details

- Application specific technologies and operational processes

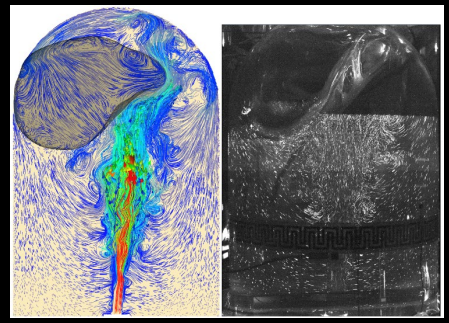


INTEGRATED OPERATIONS / PREDICTIVE PERFORMANCE

- Fluid property knowledge gaps
- Instrumentation
- Model development and validation for both high and low fidelity applications

KEY Design Details

- Zero-G Mass Gauging
- Operational and predictive fluid dynamics and thermodynamics

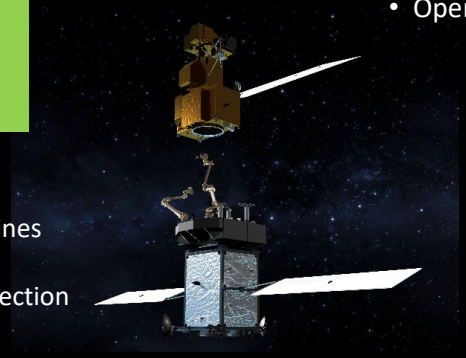


TRANSFER

- **Component brassboard** hardware **ground testing only**

Key Design Details

- Pump or pressure driven transfer
- High efficiency chill down of tank and lines
- Active cooling
- Low-leakage valves/actuators, leak detection
- Phase separation/Liquid acquisition



CFM Critical Technologies Current Investments

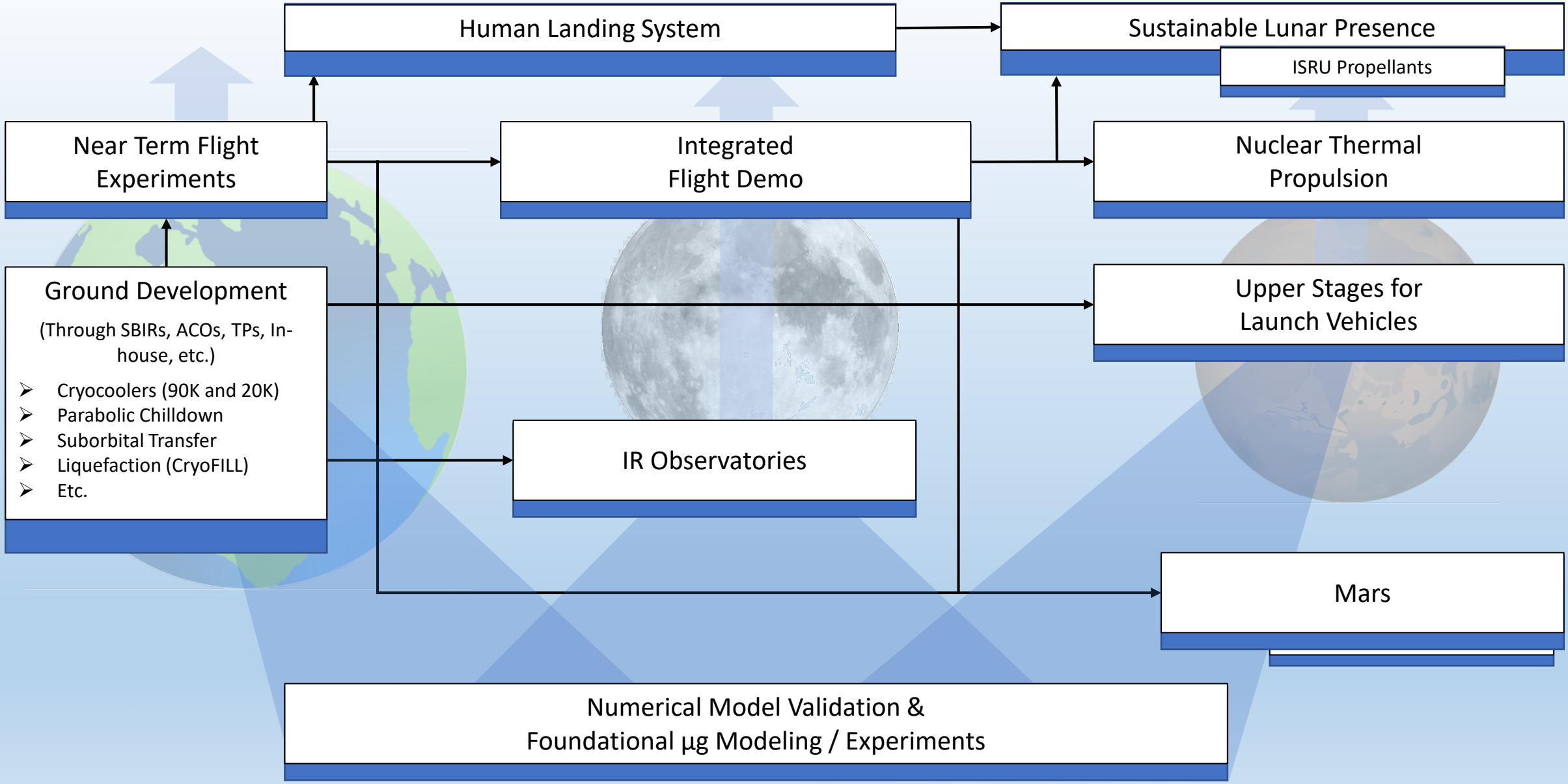
CFM Critical Technology Gaps	Cross Cutting or Fluid Specific	Current TRL	Gap Addressed**
Low Conductivity Structures	Cross Cutting	6	Tipping Point (TP)
High Vacuum Multilayer Insulation	Cross Cutting	6	FY20 TP
Sun Shields (deployment mechanism)	Cross Cutting	5	JWST / TP
Tube-On-Shield BAC	Cross Cutting	5	TP, In-house
Valves, Actuators & Components	Cross Cutting	4-5	TP, In-house
Vapor Cooling	Fluid Specific	6	TP, In-house
Propellant Densification	Fluid Specific	5	TP, In-house
Unsettled Liquid Mass Gauging, multiple methods	Cross Cutting	4-7	TP, ECI, FO, In-house
Sub-surface Helium Pressurization in Micro-g	Cross Cutting	5	ZBOT / TP
Line Chilldown (MPS, iRCS, Transfer)	Cross Cutting	5	TP
Pump Based Mixing	Cross Cutting	5	ZBOT / TP
Thermodynamic Vent System	Cross Cutting	5	TP
Tube-On-Tank BAC	Cross Cutting	5	In-house
Liquid Acquisition Devices	Fluid Specific	5	TP
Advanced External Insulation	Cross Cutting	4	Paragon / CELSIUS
Automated Cryo-Couplers	Cross Cutting	4	TPs, HLS, ECI
Cryogenic Thermal Coating	Cross Cutting	4	TP, In-house
High Capacity, High Efficiency Cryocoolers 90K	Cross Cutting	4	In-house
Soft Vacuum Insulation	Cross Cutting	3	MAV (MSR)
Structural Heat Load Reduction	Cross Cutting	3	CIF
Propellant Tank Chilldown	Cross Cutting	4	FY20 TP
Transfer Operations	Cross Cutting	4	FY20 TP
High Capacity, High Efficiency Cryocoolers 20K	Fluid Specific	4	In-house
Liquefaction Operations (MAV & ISRU)	Fluid Specific	4	TP / In-house
Para to Ortho Cooling	Fluid Specific	4	TP
Cryogenic Flow Meter	Both	4	TP w/o data rights
Autogenous Pressurization in Micro-g*	Fluid Specific	4	ZBOT / TP
CFM Modeling Capability			ZBOT, In-house, STRG, FO

- NASAs CFM Portfolio has contributed extensively to bringing CFM critical technologies to TRL 4-6
- Significant SBIR program leverage
- Nearly all are receiving active investments
- Recent focus has been on advancing the CFM component and subsystem technologies beyond the mid-range TRL level and developing integrated flight demonstrations to support NASAs future missions
- Future focus will be closing out the current lower TRL investments and development of the near-term flight demonstrations
- HLS Leverage for multiple components
- SMD ZBOT demonstrations and model validation
- High to low fidelity model development and validation to predict future mission capabilities

* Note:Traditional settled pressurization methods TRL 9

** Note: Addressing the gap does not in all cases equate to gap closure; some gaps are fluid or architecture specific; the goal is to develop high-fidelity models to support mission designs.

Long Term CFM Strategy and End User Applications



CFM Investment Approach

Ground Development (Current CFM Projects)

- Multiple ground-based component and subassembly projects addressing the CFM critical technologies
- Many of these lower-level capability demonstrations are advanced in technology readiness through the Tipping Point integrated system demonstrations
- CFM technologies supporting ISRU architectures do not require micro-g and TRL can be advanced to 6/7 in ground testing.

Near-Term Demonstrations (FY20 Tipping Points)

- STMD is sponsoring a significant Tipping point award to incentivize Industry to fly CFM experiments that will combine many of these CFM technologies to develop and raise the TRL level of storage and transfer
- Four flight demonstrations have been selected for award and are expected to fly by 2025
- Significant technology maturation is stalled in wait of integrated system and/or relevant environment testing

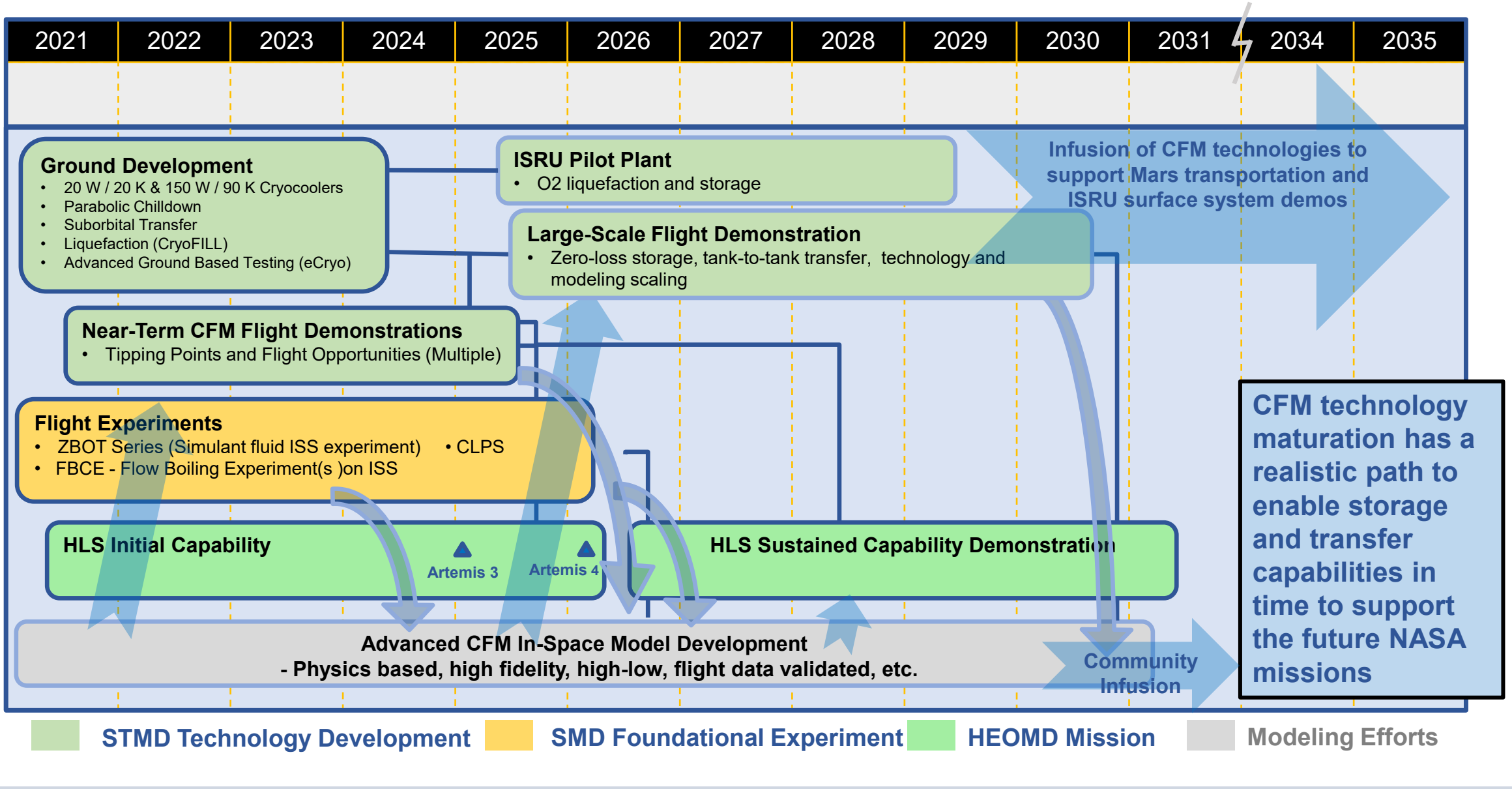
Leverage the Human Landing System (HLS) Development and Demonstration

Large Integrated Flight Demonstration

- Utilizing the data and performance gathered during the Near-Term Demonstrations and other mature enabling and enhancing technologies, the CFM individual systems will be demonstrated in a scalable flight experiment directly addressing the performance needs of CFM stakeholders.
- Post flight, CFM technologies will be ready to support NTP and other deep space Cryo stage missions

Operations Optimization

CFM Notional Near-Term Roadmap



Capability Gap Performance Goals

Storage

- Lunar Human Return/Exploration: Cryogenic propellant storage with near zero boil-off dependent on architecture and mission duration; LOx, LCH_4, LH_2
- Long Term Lunar/Mars/ISRU: Zero Boil-off (net head load of less than zero); LOx, LCH_4, LH_2; includes thermal insulation and structural interfaces limiting heat leak into tanks

Transfer

- Propellant losses of 1% (TBR) or less during transfer activity
- <1% (TBR) residual in supply tank

Liquefaction

- Integrated system performance of 2 kg/hr of O_2 and 0.3 kg/hr of H_2
- Fluids to demonstrate: LOx, LCH_4, LH_2

Predictive Model Validation

- Demonstrate that the relative difference between CFD or nodal model results and test data is less than 15% (TBR) for pressure time histories and less than 30% (TBR) for (fluid and/or wall) temperature time histories
    - Sufficient for acceptable performance margin (TBD) of operational systems


EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION
GO – Advanced Propulsion



SPACE FLIGHT ARCHITECTURE DOMAINS

Science, Exploration, Commerce & Security

LEO TO CIS-LUNAR

CLPS/Artemis & Cis-Lunar Development

- Science Payloads
- Mining & Resource Extraction
- Manufacturing
- Fuel Depots / In Situ Derived Prop
- Space Solar Power
- Outposts (In-Space & Surface)
- Tourism
- Planetary Defense Assets
- Rule of Law Compliance Assets
- National Security Space Assets

MESO-SOLAR

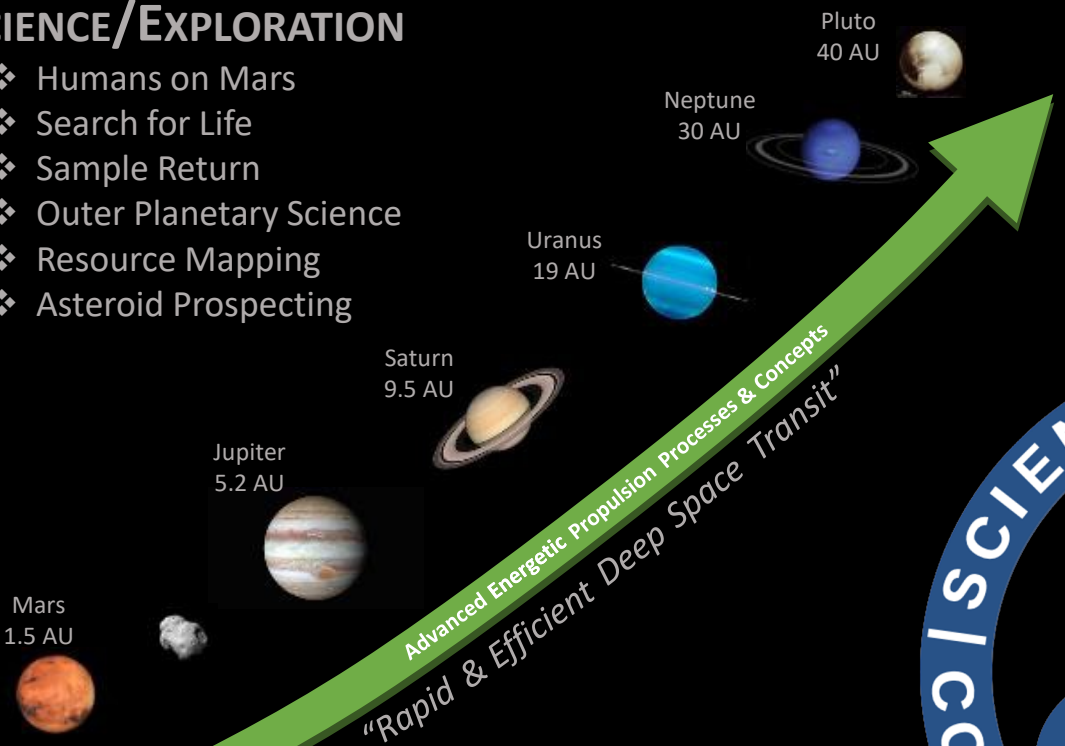
Moon-to-Mars & Expanding Science/Exploration

- Humans on Mars
- Search for Life
- Sample Return
- Outer Planetary Science
- Resource Mapping
- Asteroid Prospecting

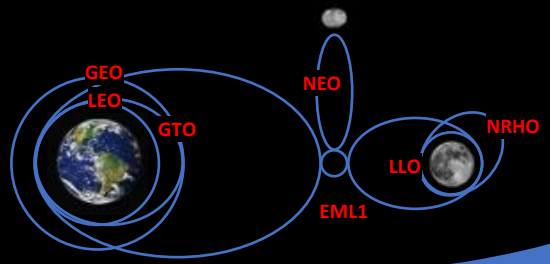
EXTRA-SOLAR

Outer Solar System & Interstellar

KBOs & Primitive Bodies	>50 AU
Heliosphere / Local ISM	100-200 AU
Pristine ISM	200-400 AU
Solar Gravity Lens	500-800 AU
Nearby Stars / Exoplanets	4.5-20 LY



"Commercially Sustained Cis-Lunar Infrastructure"



CP | SEP | NTP | NEP

"Littoral & Blue Water Mobility Analog"



STMD STRATEGIC FRAMEWORK ENVISIONED FUTURE

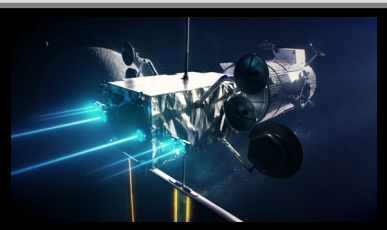
GO Thrust – Advanced Propulsion Vision

Produce advanced propulsion technologies that enable future science/commercial/exploration missions

Developing advanced propulsion technologies to push the cutting edge farther and faster than ever before

Architecture Driven Propulsion Technologies

Science/Exploration/Commerce/Security Capabilities



High-ΔV EP Spacecraft

High-ΔV XX-kWe EP Capability

- 12-kWe Class HET → Gateway/PPE SEP
- 7-14-kWe Class GIT → Advanced NEXT
- 100-kWe Class Electric Thrusters including HET, MPD, VASIMR, & other options → Mars Transportation System



Outer Planetary Robotic NEP Spacecraft

Deep Space Nuclear Flagship Capabilities

- Propulsion Technologies Enabling Nuclear Propulsion Robotic Spacecraft
  - Fission Surface Power Derived NEP
  - Dynamic-RPS Derived NEP
  - Advanced LCF Derived NEP



Earth Pole Sitting Observatories



Sun Pole Sitting Observatories

Observational Platforms for Science, Commercial & Security Missions Requiring Unlimited ΔV Capability

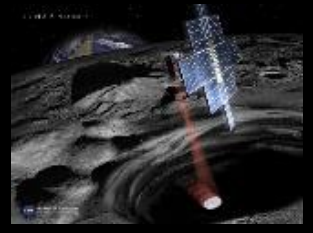
- Solar Sail Development & Demonstration
  - Monitor Solar Cruiser Project
  - Supplement SMD Technology Development as Warranted
  - Support Early-Stage Concept R&D



High-ΔV ESPA-Class Deep Space Spacecraft

Small Spacecraft Science, Commercial & Security Missions Requiring High-ΔV EP Capability

- Focus on ESPA-Class Sub-kW EP
- Flight Qualify & Demonstrate
- SMD SIMPLEx Mission Infusion



Green Propellant Deep Space Spacecraft

Green Propellant Adoption & Infusion into Missions of Opportunity

- Facilitate Provider/User Transition
- Incentivize Mission Opportunities
- Lunar Flashlight Mission Infusion



Thruster Advancement for Low Temperature Ops in Space

Deep Space Science Missions Requiring Cold Tolerant Storable Propulsion for Extreme Environments Access

- MON-25/MMH Bipropellant Thruster Technology
- Compact Lander Propulsion – TALOS → CLPS Infusion
- Deep Space Variant – Extensible TALOS → Enceladus

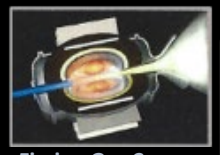
Inspiration Driven Research

Transformational Capabilities

Sustained investment in Advanced Energetic Propulsion research & innovation enables the possibility for new breakthrough technologies



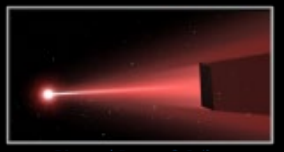
Low-α NEP



Fission Gas Core or Advanced Solid Core



Pulsed Fission



Directed Energy & Sails



Fusion



Antimatter



Breakthrough Science

Capability Goals:

- **α ≤ 5 kg/kW**
- **Thrust-to-Weight ≥ 0.6**
- **Relativistic S/C Velocity ≥ 0.1c**

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

ADVANCED PROPULSION CAPABILITY OUTCOMES

Propulsion Technology Development Streams

Exploration Architecture Systems Development

Lunar Gateway

E1: Gateway/PPE SEP

Develop 12.5-kWe SEP string and enable 50-kWe thruster array for lunar orbit maneuvering and NRHO station keeping

Artemis/Mars

E2: Cryogenic CP

Affordable, highly reusable cryogenic propulsion to provide in-space transport and lunar surface access with extensibility to Mars

Mars Transport

E3-A: NEP/CP Hybrid

Multi-MW NEP to provide cruise ΔV plus affordable & highly reusable cryogenic propulsion to provide gravity well ΔV

E3-B: NTP

High thrust NTP to provide gravity well ΔV plus reactor integrated OMS to provide supplemental ΔV

TRL 6-9

Science, Commerce & Security Technology Development

Flagship SEP

S1: High-ΔV SEP

Develop 7-14 kWe gridded ion EP string to enable more ambitious very high-ΔV deep space robotic missions

Extreme Access Storable Propulsion

S2-A: Baseline TALOS

Baseline TALOS: In-space cold tolerant storable pulse-mode bi-propulsion to enable extreme environment surface access

S2-B: Extensible TALOS

Extensible TALOS: Deep space variant modifications & qualification for high-throughput, long-burn orbit transfer and extreme access

High-ΔV Small S/C

S3: ESPA Sub-kW SEP

Fully flight qualified high-throughput, radiation-tolerant sub-kW Xenon HET enabling high-ΔV ESPA-class deep space missions

Unique Platforms

S4: Solar Sail

Matured solar sail technology to provide essentially unlimited S/C ΔV as an enabler of unique platform capabilities

Green Prop Adoption

S5: Green Propulsion

Facilitate green propellant infusion by incentivizing mission adoption and PPP opportunities to mature a wide range of thrust classes

TRL 6-9

Transformational Capability R&D

Transformational CP

T1: RDRE

Early-stage R&D focused on RDRE maturation & prototype demonstrations to achieve transformational gains in CP performance for launch, in-space, and lander systems

Flagship NEP

T2: Robotic S/C NEP

Propulsion technologies enabling low-to-moderate power NEP transportation systems (FSP/Dynamic-RPS/LCF Derived NEP)

Rapid Transit Interstellar Probe

T3: Near Sun STP

Early-stage R&D focusing on transformational STP capability to enable solar perihelion burn Oberth maneuvers and the attainment of high solar system escape velocities

Advanced Energetic Propulsion

T4: Fusion/AEP Concepts

Early-stage R&D focused on rapid prototype demonstration of nuclear fusion propulsion technologies and AEP concepts to achieve transformational capabilities for fast & efficient solar system wide access

TRL 3-6

2020 2025 2030

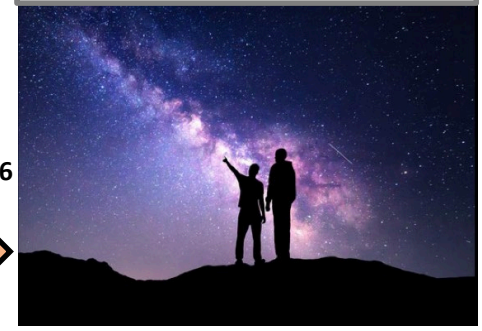
Exploration Architectures



Science, Commerce & Security

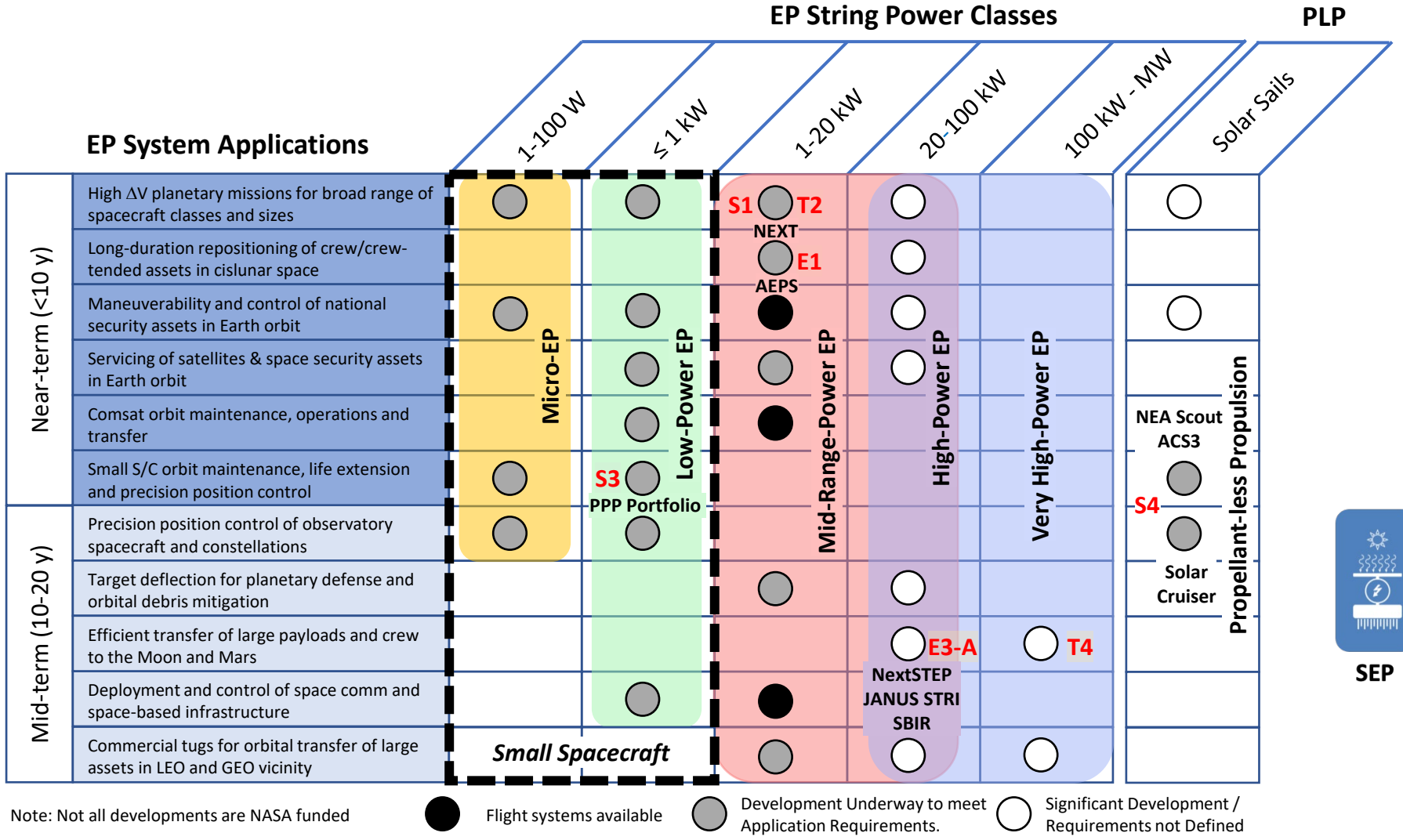


Inspiration Driven Research



SOA – ELECTRIC PROPULSION SYSTEMS

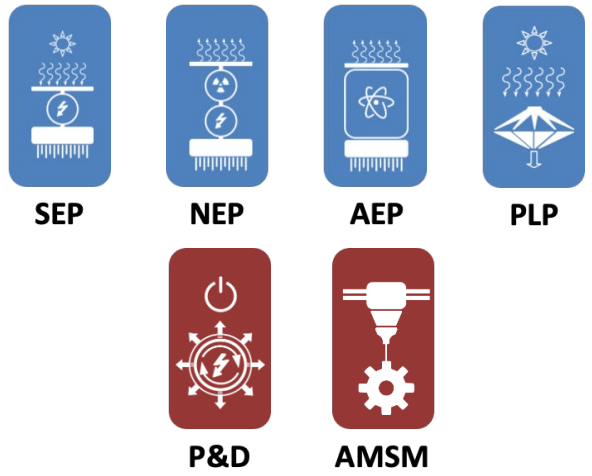
Historical Developments & Projected Capabilities



Technology Objective Index

E1	Gateway/PPE SEP
E2	Cryogenic Propulsion
E3-A	Mars NEP/CP Hybrid
E3-B	Mars NTP
S1	Advanced NEXT SEP
S2-A	Baseline TALOS
S2-B	Extensible TALOS
S3	ESPA Sub-kW SEP
S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements



SOA – CHEMICAL & THERMAL PROPULSION SYSTEMS

Historical Developments & Projected Capabilities



Thermal Propulsion Families

In-Space CP Applications	Solid Propellant (Ispvac = 275 – 290 s)	Hydrocarbon HC/Hybrid (Ispvac = 320 – 340 s)	LOX/LCH4 (Ispvac = 340 – 365 s)	LOX/LH2 (Ispvac = 415 – 445 s)	MON/MMH (Ispvac = 315 – 340 s)	Green Monoprop (Ispvac = 220 – 250 s)	NTP/STP – LH2 (Ispvac = 900 – 1000 s)	RDRE (≥5% Increase Ispvac)
High Thrust (Pump-Fed)								
Large ΔV, Fixed Thrust Surface Ascent					XLR-132/RS-72 Heritage			Interagency RDRE Council
Large ΔV, Variable Thrust Descent, Hover & Landing					XLR-132/RS-72 Heritage			T1 RDRE STRG/ACO Portfolio
Limited ΔV, Fixed Thrust In-Space Transfer					XLR-132/RS-72 Heritage		E3-B SNP Project	T1 RDRE STRG/ACO Portfolio
Low-to-Moderate Thrust (Pressure-Fed)								
Large ΔV, Fixed Thrust Surface Ascent	Mars Sample Return		Cryogenic Propulsion Industry Capabilities		Apollo Heritage			
Large ΔV, Variable Thrust Descent, Hover & Landing			Cryogenic Propulsion Industry Capabilities		Apollo Heritage	Lunar Flashlight		
Reaction/Attitude Control Systems			Cryogenic Propulsion Industry Capabilities		Low MON Heritage	S5		
Limited ΔV, Fixed Thrust In-Space Transfer			E2 Artemis/HLS		S2-A / S2-B TALOS	GPIM	T3 Interstellar Probe APL IRAD	

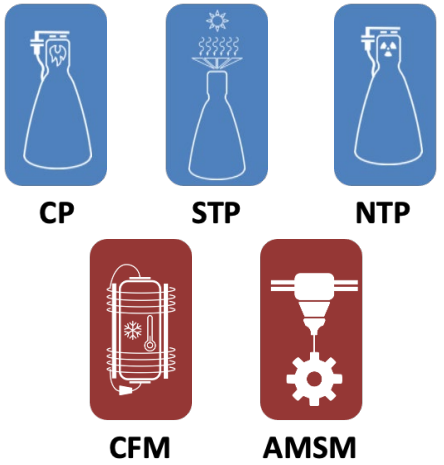
Note: Not all developments are NASA funded

- Flight System Available
- Flight System Out of Production
- Development Underway to meet Application Requirements
- Significant Development / Requirements Not Defined

Technology Objective Index

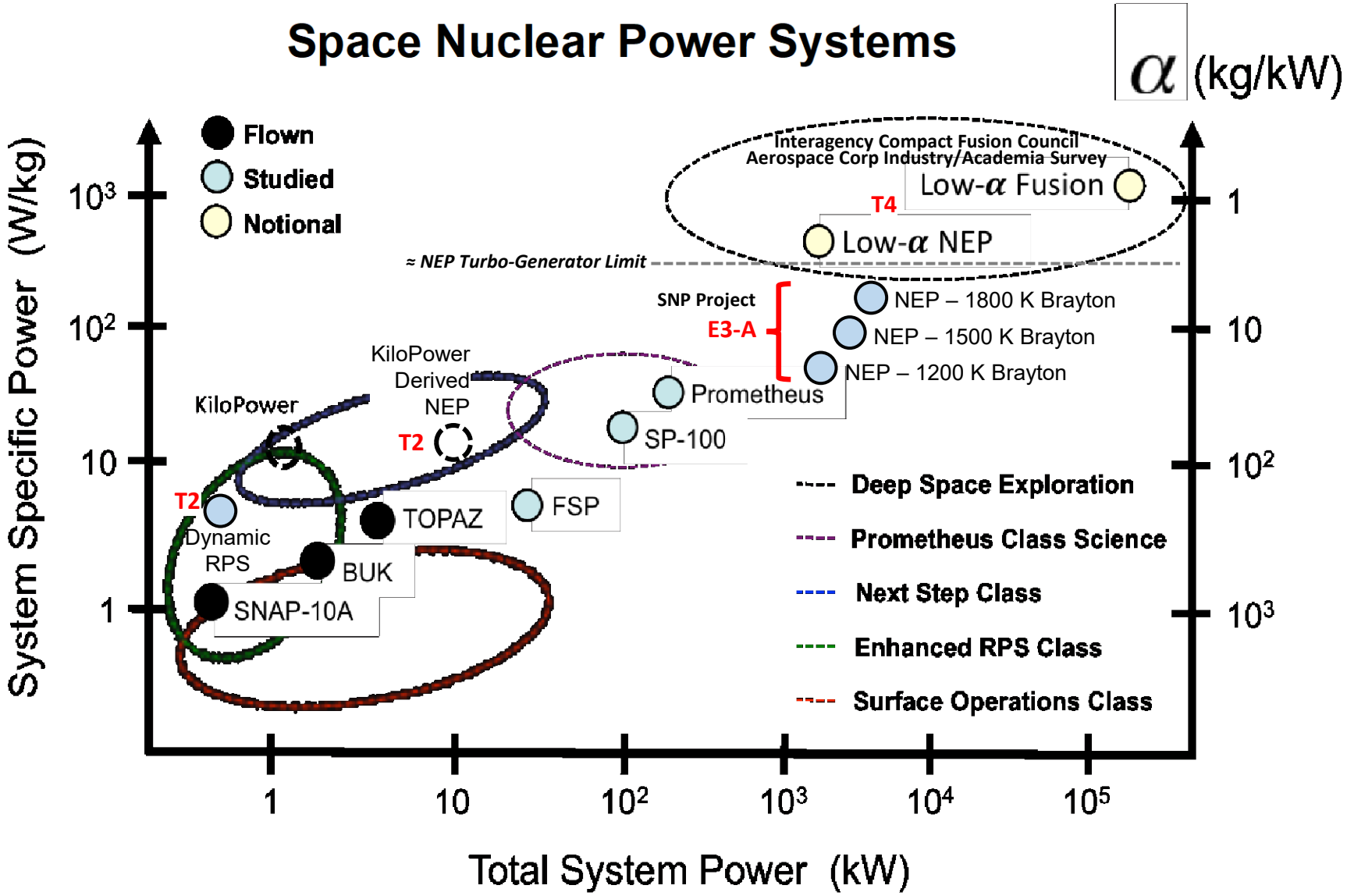
E1	Gateway/PPE SEP
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S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements



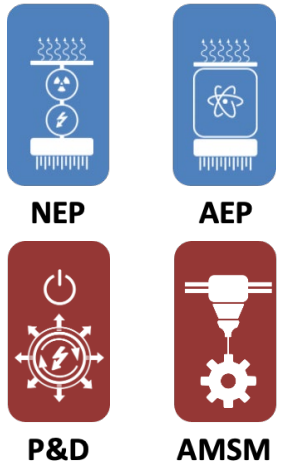
SOA – SPACE NUCLEAR PROPULSION & POWER SYSTEMS

Historical Developments & Projected Capabilities



Technology Objective Index	
E1	Gateway/PPE SEP
E2	Cryogenic Propulsion
E3-A	Mars NEP/CP Hybrid
E3-B	Mars NTP
S1	Advanced NEXT SEP
S2-A	Baseline TALOS
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S4	Solar Sail Propulsion
S5	Green Propellant
T1	RDRE Propulsion
T2	Flagship NEP
T3	Interstellar Probe STP
T4	Fusion/AEP

Technology Elements





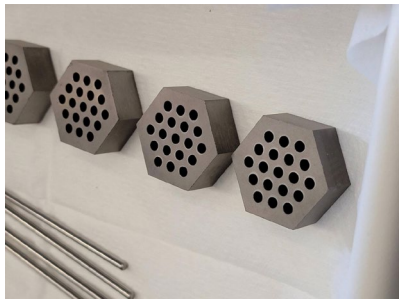
CONCLUSIONS & HIGH LEVEL DEVELOPMENT STRATEGY

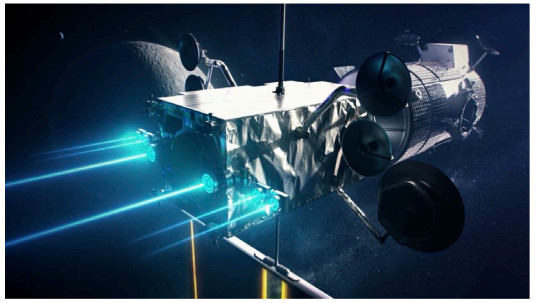
- **Architecture Driven Propulsion Technology Strategy is Essentially On Track**
  - Emphasis on sustained portfolio execution & commitment to deliveries, including accommodation of ground infrastructure impacts
  - Additional mid-TRL investment is needed in a few priority areas (e.g., ESPA-Class Sub-kW EP & Beyond NextSTEP High-Power EP)
- **Transformational Capability R&D Portfolio in need of Programmatic Restructuring & Significant Funding Augmentation**
- **High Level Development Strategy**

Architectural Outcome	Technology Capability Goal	Recommended Action	Investment Trend
Gateway/PPE SEP	12 kWe HET String / 50 kW SEP System	Sustain Execution & Commitment to PPE/Gateway Delivery	Sustain
Flagship High-ΔV SEP	7-14 kWe Gridded Ion EP String	Develop Advanced NEXT via Interagency Collaboration + SBIR + PPP	Augment
High-Power Exploration NEP	100 kWe HET, MPD, VASIMR, etc.	Industry Led Dev/Qual via STRG + SBIR + PPP (i.e., Beyond NextSTEP)	Augment
ESPA-Class High-ΔV SEP	0.5-1 kWe (nominal) EP String	Industry Led Dev/Qual/Demo via SST/GCD PPP	Augment
Extreme Cold Environment CP	Baseline MON25/MMH TALOS	Sustain Execution & Commitment to PPP CLPS Delivery	Sustain
	Deep Space Variant TALOS	Commit to Industry Led Development/Qualification via PPP	Augment
Green Propellant CP	Reduced Cost / Expanded Thrust Range	Facilitate Infusion & Industry Led Development via SBIR/STTR + PPP + Incentives	Sustain
Unlimited ΔV Platforms PLP	Flight Demonstrated Solar Sail Technology	Monitor Solar Cruiser + Supplemental Tech Dev + SBIR/STTR + Early-Stage R&D	Sustain
RDRE CP	Transformative CP Performance	Sustain Early-Stage R&D & Transition to FY23 Mid-TRL Prototype Development	Augment
Flagship NEP	Transformative Robotic Science NEP	Evaluate/Facilitate FSP/Dynamic-RPS/LCF NEP System Integration & Maturation	Augment
Interstellar Probe Near Sun STP	Transformative Near Sun STP Capability	Sustain Early-Stage R&D & Transition to FY23 Mid-TRL Prototype Development	Augment
Fusion/AEP Concepts	Transformative Fusion/AEP Capability	Establish Comprehensive Nuclear Fusion/AEP Early-Stage R&D Portfolio	Augment

SUMMARY / NEAR-TERM PRIORITIES

- Space Nuclear Propulsion
  - High Temperature Fuel Maturation for NTP
  - Subsystem prototyping and thermal control investments for NEP
- Cryogenic Fluid Management
  - Multiple integrated system demonstrations
  - Modeling development and validation
- Advanced Propulsion
  - Complete on-going projects with program dependency
    - TALOS, PPE Elements
  - SubkW Electric Propulsion – SMD Enabling
  - Balance of transformational propulsion investments





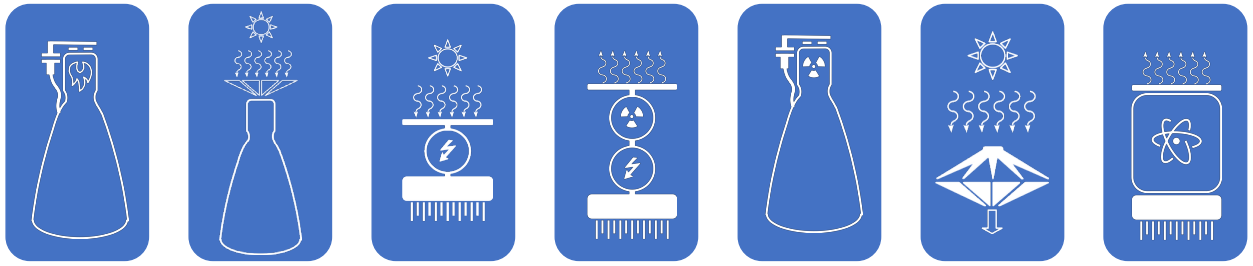


Backup

ADVANCED PROPULSION TECHNOLOGY DOMAIN

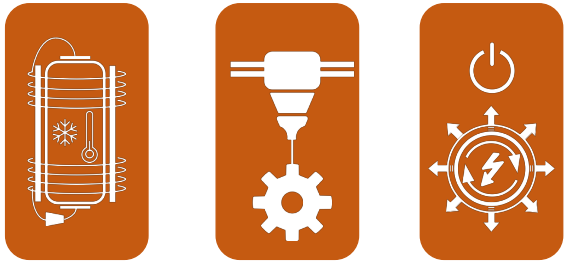
Taxonomy & Acronym Glossary

PROPULSION TECHNOLOGIES



CP STP SEP NEP NTP PLP AEP

CROSS-CUTTING SUPPORT TECHNOLOGIES



CFM AMSM P&D

ACRONYMS

AEP – Advanced Energetic Propulsion
ACO – Announcement of Collaborative Opportunity
ACS – Attitude Control System
AMSM – Advanced Materials, Structures & Manufacturing
AU – Astronomical Units
CP – Chemical Propulsion
CFM – Cryogenic Fluid Management
CLPS – Commercial Lunar Payload Services
EML1 – Earth Moon Lagrange Point 1
ESPA – Evolved Secondary Payload Adaptor
FSP – Fission Surface Power
GCD – Games Changing Development (Program)
GEO – Geo Synchronous Orbit
GIT – Gridded Ion Thruster
GTO – Geo Transfer Orbit
HET – Hall Effect Thruster
ISM – Interstellar Medium
LCF – Lattice Confined Fusion
LEO – Low Earth Orbit
LLO – Low Lunar Orbit
LY – Light Year
MMH – Mono-Methyl Hydrazine
MON – Mixed Oxides of Nitrogen
MPD – Magneto Plasma Dynamic (Thruster)
MPS – Main Propulsion System
NEA – Near Earth Asteroid
NEO – Near Earth Object
NEP – Nuclear Electric Propulsion
NEXT – Next Evolutionary Xenon Thruster
NRHO – Near Rectilinear Halo Orbit
NTP – Nuclear Thermal Propulsion
PLP – Propellant-Less Propulsion
PPE – Propulsion & Power Element (Foundational Gateway)
PPP – Public Private Partnership
PPU – Power Processing Unit
P&D – Power & Distribution
RCS – Reaction Control System
RDRE – Rotating Detonation Rocket Engine
RPS – Radioisotope Power System
SBIR – Small Business Innovation Research (Program)
S/C – Spacecraft
SEP – Solar Electric Propulsion
SOA – State of Art
SNP – Space Nuclear Propulsion (Project)
SST – Small Spacecraft Technology (Program)
STP – Solar Thermal Propulsion
TALOS – Thruster Advancement for Low Temperature Operations in Space
TDM – Technology Demonstration Mission (Program)
TP – Tipping Point
TRL – Technology Readiness Level
T/W – Thrust-to-Weight (ratio)
VASIMR – Variable Specific impulse Magnetoplasma Rocket
ZBO – Zero Boil Off
α – System Specific Mass (kg/kW)
ΔV – Spacecraft Velocity Change