National Aeronautics and
Space Administration

Space Technology Mission Directorate

JANNAF 2021

JPM/PIB/MSS/LPS/SPS MEETING

Session 3A – WORKSHOP

Discernment of a Joint Approach to Identify & Select Advanced Concepts for Transformative Impact

Transformational Propulsion Research & Technology Strategy

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Principal Technologist for Propulsion
NASA/STMD | HQ

June 2021

www.nasa.gov/spacetech

STMD STRATEGIC FRAMEWORK

A Data Driven Space Technology Investment Portfolio

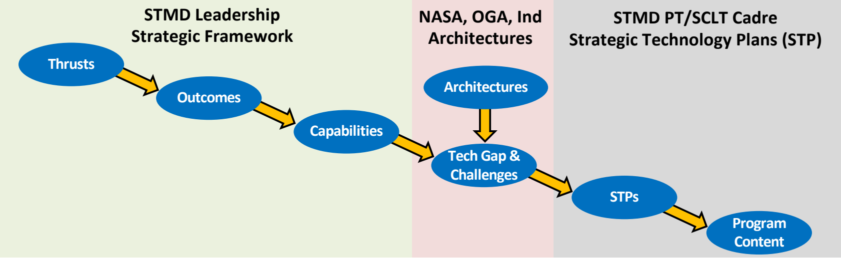
STMD STRATEGIC FRAMEWORK

Thrusts	Space Technologies
Go *Rapid, Safe, & 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
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • 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 Life Support & Human Performance 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.

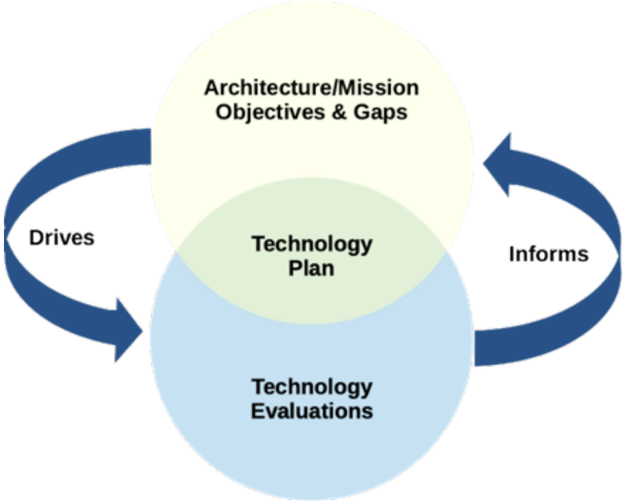
SPACE TECHNOLOGY PORTFOLIO FORMULATION



STMD Leadership Strategic Framework

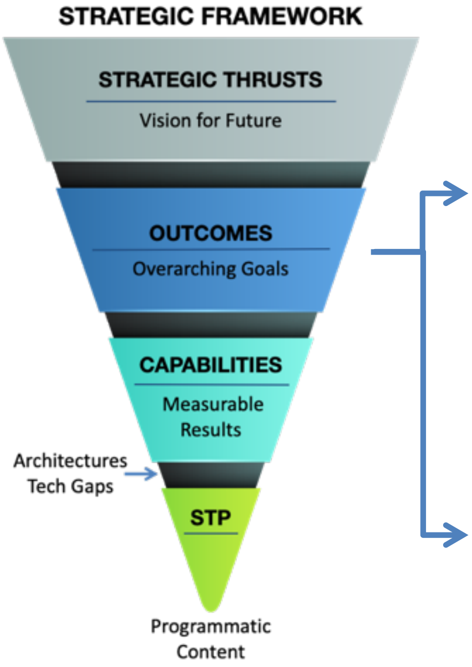
NASA, OGA, Ind Architectures

STMD PT/SCLT Cadre Strategic Technology Plans (STP)



GO THRUST

Overarching Strategic Goals



STRATEGIC FRAMEWORK

STRATEGIC THRUSTS
Vision for Future

OUTCOMES
Overarching Goals

CAPABILITIES
Measurable Results

Architectures
Tech Gaps

STP

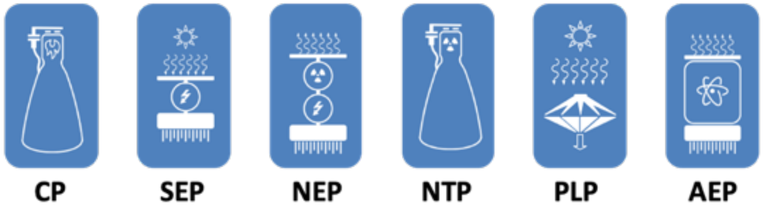
Programmatic
Content

	2020s	2030s	2040s
Space Access	• Multiple Highly-Reusable Commercial Launch Services (CLV) Fleets Supporting Space Science, Exploration, Commerce, and Security • Multiple Affordable, Dedicated, Responsive Small Launcher Services Fleets for Orbital Delivery of Next Generation Small Spacecraft Platforms • Development of Alternative High-Speed Propulsion Technologies and Integrated Space Access Concepts	• CLV Launch Costs Reduced by Order of Magnitude Supporting Increased Mission Utility & Market Growth • Dedicated, Responsive Small Spacecraft Space Access Costs Reduced by 50% Supporting Increased Mission Utility & Market Growth • Demonstration of Alternative High-Speed Propulsion Systems and Integrated Space Access Concepts	• Robust Commercially-Sustained Up/Down Transportation Market Underpinning a Vibrant and Dynamic Space Economy • Establish Routine Commercially-Sustained Airport-Like Launch Operations with Broad Based User Community • Introduction of Integrated High-Speed Propulsion Space Access Systems to CLV Fleets
In-Space Transportation	• Introduction of Compact, Reduced-Cost Cold Tolerant In-Space Storable Propulsion Systems for Long-Duration, Extreme Environments Operation • Accelerated Adoption & Deployment of Reduced-Cost Advanced Manufactured In-Space Cryogenic Liquid Propulsion Systems • Flight Demonstration and Introduction of Mid-Range-Power EP System (7-14 kW Strings) Serving Exploration, Science, Commerce and Security Needs • Introduction of Rad-Tolerant, High ΔV, Sub-kW EP Systems Enabling Small S/C Deep Space Missions • Development & Flight Demonstration of Space Nuclear Propulsion (SNP) Systems (NTP &/or NEP) Establishing Viability, Feasibility, and Affordability • Sustained Research and Initial Proof-of-Principle Demonstrations of Advanced Energetic Propulsion Technologies to Enable Ambitious Missions Throughout the Solar System & Beyond	• Widespread Adoption and Infusion of Green Propellant Propulsion Systems & Introduction of Rotating Detonation Rocket Engines • In-Space Cryogenic Liquid Propulsion Costs & Reusability Improved by an Order of Magnitude Promoting Mission Utility & Market Growth • Flight Demonstration and Introduction of High-Power EP System (50-100 kW Strings) Serving Exploration, Science, Commerce and Security Needs • Sub-kW EP Propulsion Costs and Lifetime Improved by an Order of Magnitude Promoting Mission Utility • Flight Certified SNP Systems (NTP &/or NEP) Supporting Fast Opposition-Class Human Expedition to Mars & Outer Solar System kWe-Class Science • Initial Ground Demonstration of Advanced Energetic Propulsion Technologies to Enable Short Trip Time Interplanetary Missions Throughout the Solar System & Interstellar Flight	• Thrust Scale-Up of Green Propellant Propulsion Systems, Rotating Detonation Rocket Engines, and Advanced Storable Propulsion Systems • Robust, Highly Reusable Liquid Propulsion Systems Supporting ISRU-Sustained Cis-Lunar/Mars Commercial Fleets • Introduction of Very-High-Power EP Systems (100 – 1000 kW strings) Enabling Efficient & Rapid Cis-Lunar/Mars Transportation of Cargo & Crew • Widespread Adoption of Sub-kW EP Platforms with Revolutionary Impacts on Mission Capability/Cost • Robust and Reusable SNP Transportation Systems Supporting Cis-Lunar/Mars Blue Water Mobility and Sustained Mars Exploration • Initial Breakthrough Flight Demonstration of Advanced Energetic Propulsion Technologies to Enable Short Trip Time Interplanetary Missions and Interstellar Flight

SPACE TRANSPORTATION TECHNOLOGY DEVELOPMENT STRATEGY

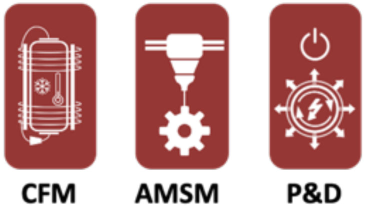
Architecture/System Drivers & Technology Taxonomy

PROPULSION TECHNOLOGY TAXONOMY



CP – Chemical Propulsion
SEP – Solar Electric Propulsion
NEP – Nuclear Electric Propulsion
NTP – Nuclear Thermal Propulsion
PLP – Propellant-Less Propulsion
AEP – Advanced Energetic Propulsion

CROSS-CUTTING SUPPORT TECHNOLOGIES



CFM – Cryogenic Fluid Management
AMSM – Advanced Materials, Structures, & Manufacturing
P&D – Power & Distribution

SPACE FLIGHT DOMAINS

Science, Exploration, Commerce & Security

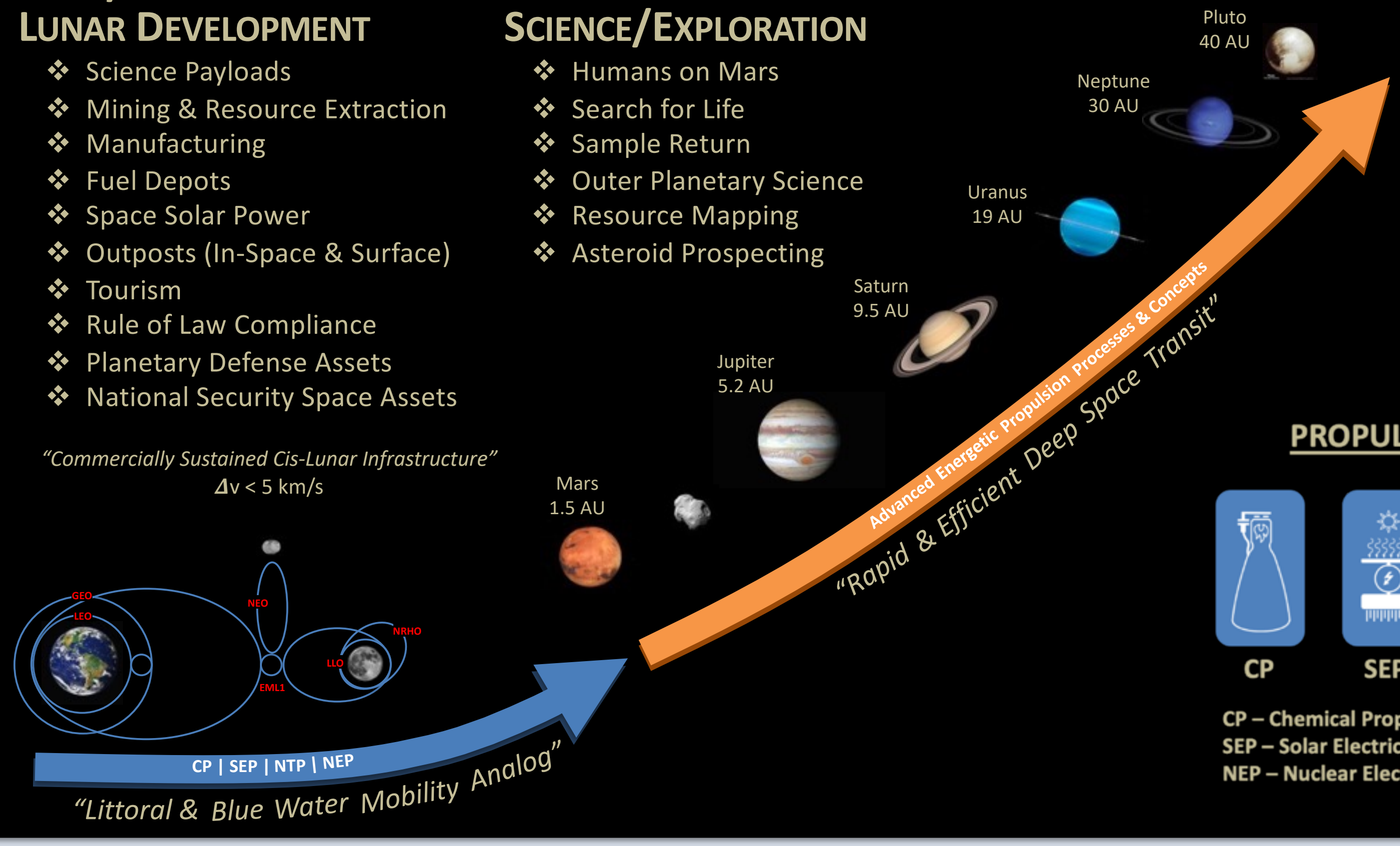
CIS-LUNAR
CLPS/ARTEMIS & CIS-LUNAR DEVELOPMENT

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

"Commercially Sustained Cis-Lunar Infrastructure"
$\Delta v < 5$ km/s

MESO-SOLAR
MOON-TO-MARS & EXPANDING SCIENCE/EXPLORATION

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



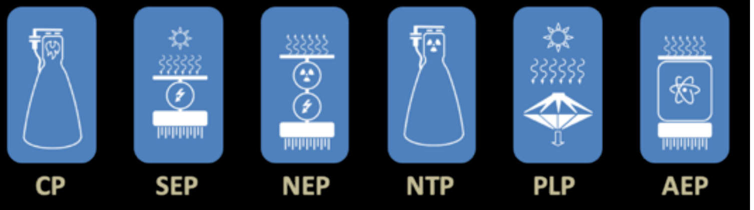
"Rapid & Efficient Deep Space Transit"

"Littoral & Blue Water Mobility Analog"

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

PROPULSION TECHNOLOGY TAXONOMY



CP – Chemical Propulsion
SEP – Solar Electric Propulsion
NEP – Nuclear Electric Propulsion
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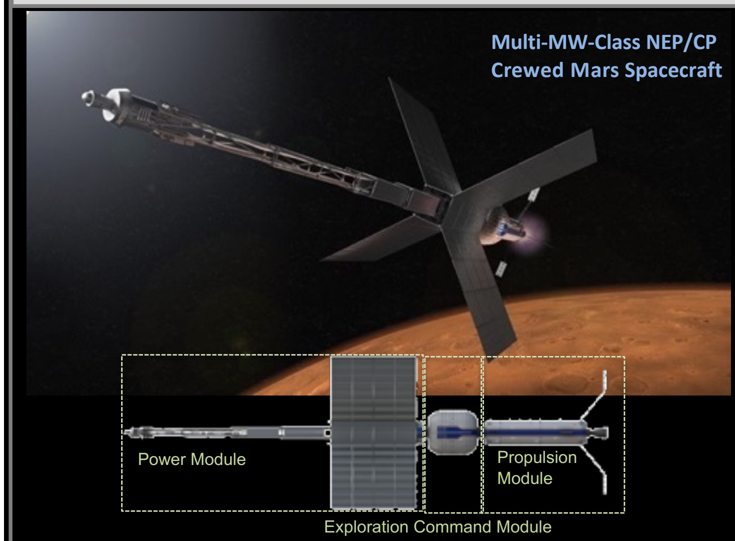
PLP – Propellant-Less Propulsion
AEP – Advanced Energetic Propulsion

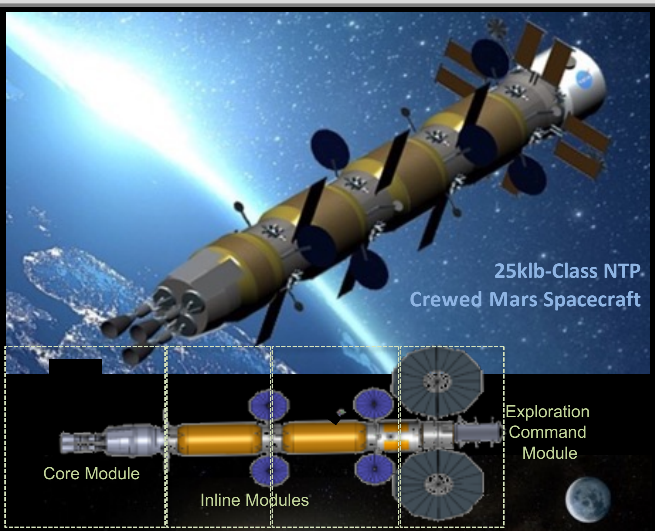
ARCHITECTURE & INNOVATION DRIVEN PROPULSION R&T

Envisioned Space Nuclear System Capabilities

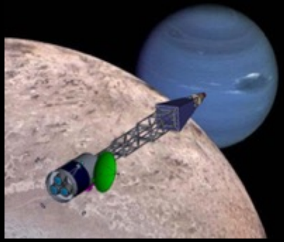
ARCHITECTURE DRIVEN NUCLEAR PROPULSION TECHNOLOGIES
SCIENCE/EXPLORATION/COMMERCE/SECURITY CAPABILITIES



Multi-MW-Class NEP/CP Crewed Mars Spacecraft



25klb-Class NTP Crewed Mars Spacecraft

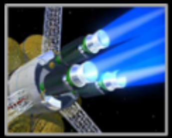


10-kW-Class NEP Neptune-Triton Spacecraft

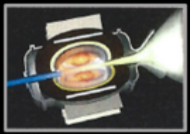
DRACO Spacecraft

INNOVATION DRIVEN RESEARCH
AEP TRANSFORMATIONAL CAPABILITIES

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

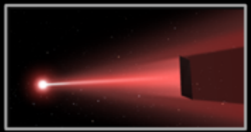


Low-α NEP



Fission Gas Core or Enhanced Solid Core

Pulsed Fission



Directed Energy & Sails

Pulsed Fusion

Antimatter

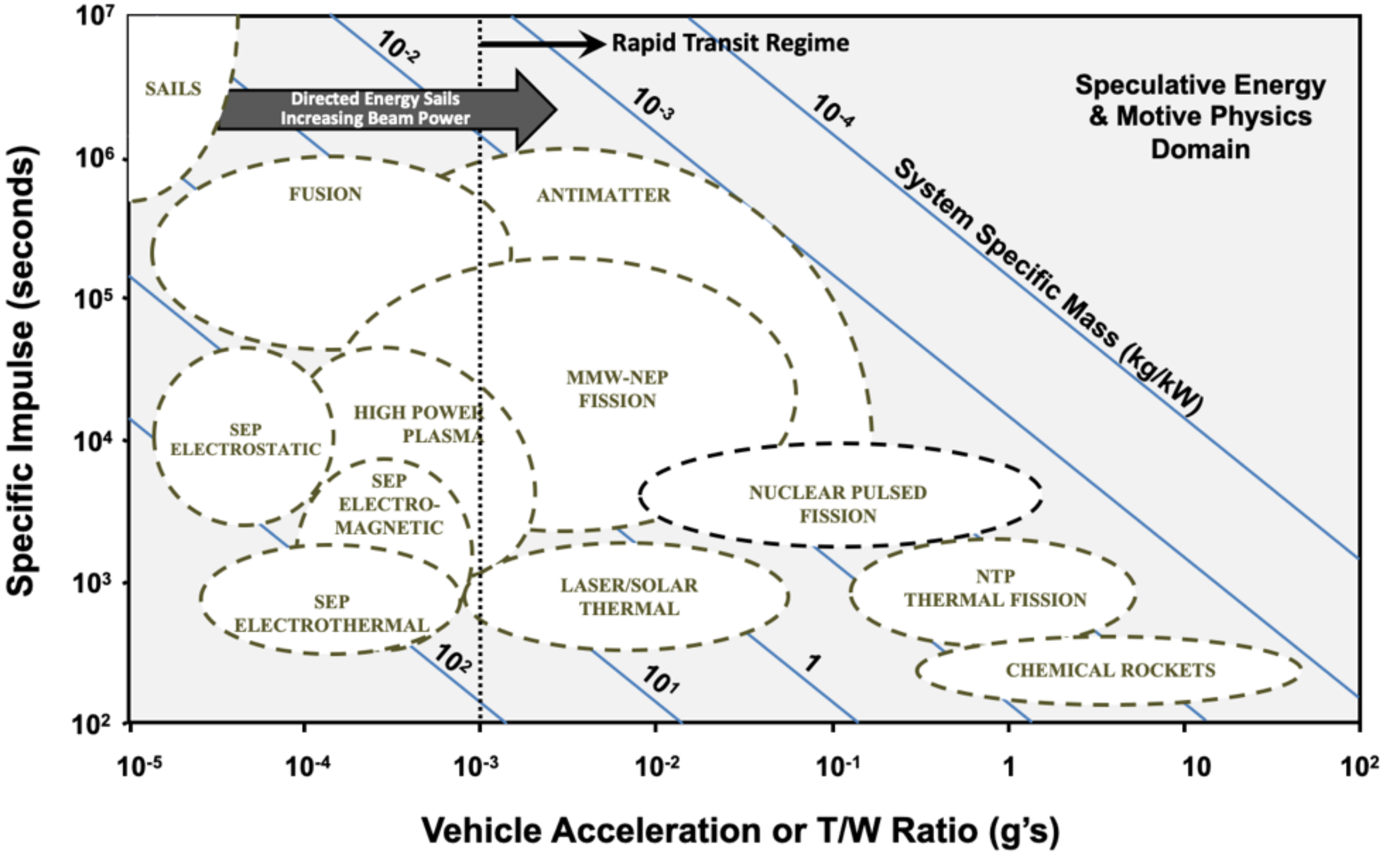
Breakthrough Science

Capability Goals:
- $\alpha \leq 5$ kg/kW
- Thrust-to-Weight ≥ 0.6
- Relativistic S/C Velocity ≥ 0.1c

ADVANCED ENERGETIC PROPULSION CAPABILITIES

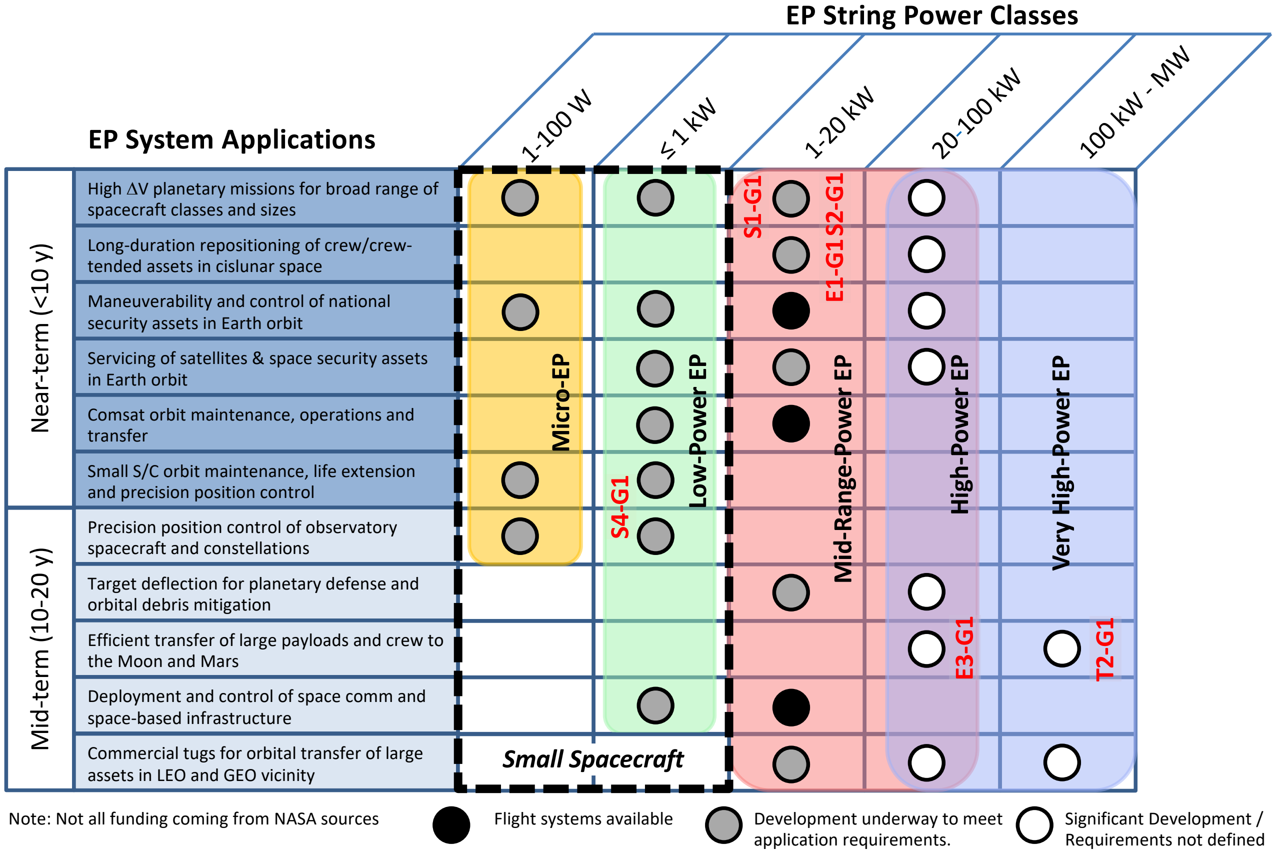
Landscape of Technology Options

The Advanced Propulsion Technology Landscape



ELECTRIC PROPULSION SYSTEMS

Historical Developments & Projected Capabilities



	EP System Applications	1-100 W	≤1 kW	1-20 kW	20-100 kW	100 kW - MW
Near-term (<10 y)	High ΔV planetary missions for broad range of spacecraft classes and sizes	◐	◐	◐	○	
	Long-duration repositioning of crew/crew-tended assets in cislunar space			◐	○	
	Maneuverability and control of national security assets in Earth orbit	◐	◐	●	○	
	Servicing of satellites & space security assets in Earth orbit		◐	◐	○	
	Comsat orbit maintenance, operations and transfer		◐	●		
	Small S/C orbit maintenance, life extension and precision position control	◐	◐			
Mid-term (10-20 y)	Precision position control of observatory spacecraft and constellations	◐	◐			
	Target deflection for planetary defense and orbital debris mitigation			◐	○	
	Efficient transfer of large payloads and crew to the Moon and Mars				○	○
	Deployment and control of space comm and space-based infrastructure		◐	●		
	Commercial tugs for orbital transfer of large assets in LEO and GEO vicinity			◐	○	○

Note: Not all funding coming from NASA sources

● Flight systems available

◐ Development underway to meet application requirements.

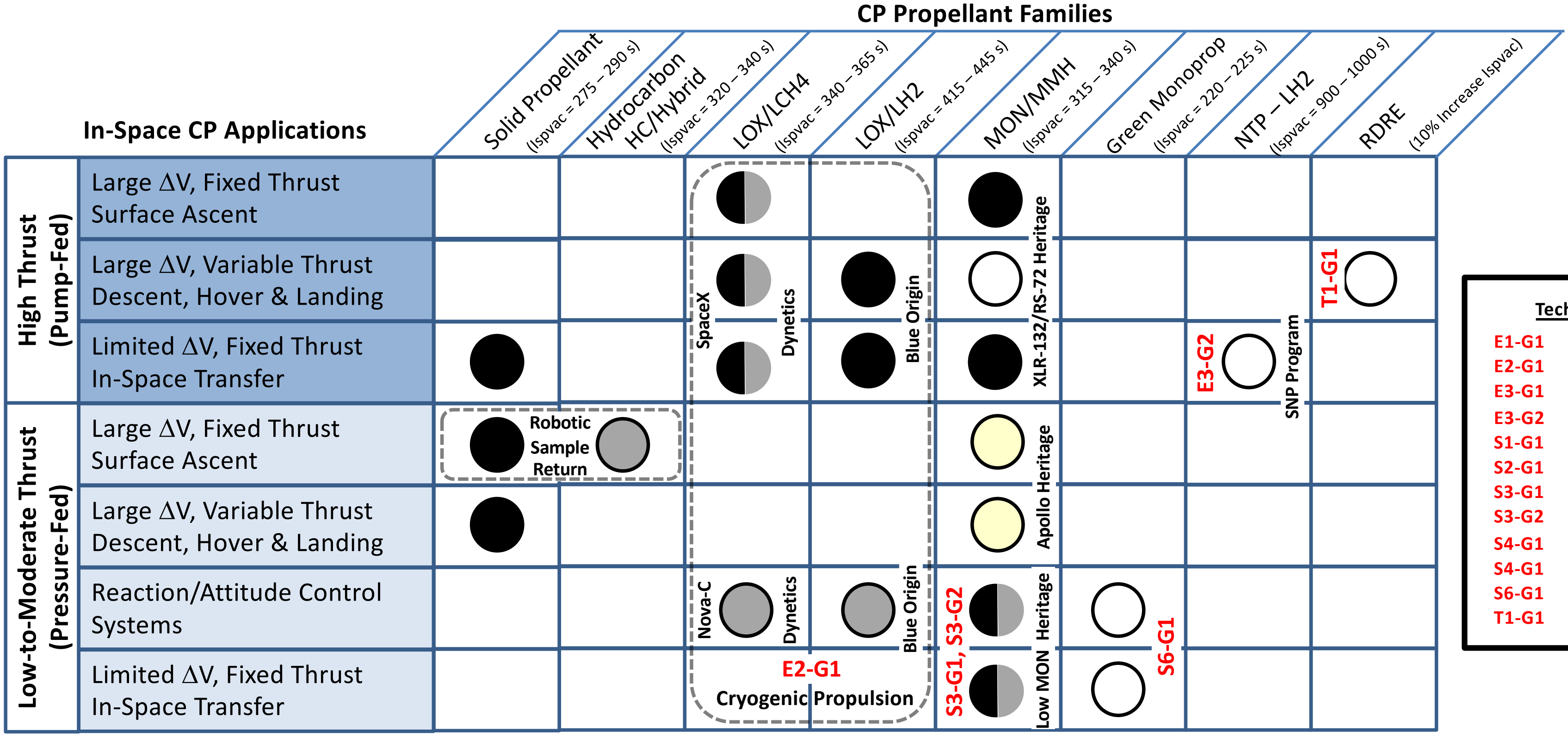
○ Significant Development / Requirements not defined

Technology Gap Index

E1-G1	Gateway PPE-SEP
E2-G1	Cryogenic Propulsion
E3-G1	NEP/CP
E3-G2	NTP
S1-G1	NEXT-C EP
S2-G1	KiloPower Derived NEP
S3-G1	Baseline TALOS
S3-G2	Extensible TALOS
S4-G1	Sub-kW SEP
S4-G1	Solar Sail Propulsion
S6-G1	Green Propellant
T2-G1	AEP

CHEMICAL PROPULSION SYSTEMS

Historical Developments & Projected Capabilities



CP Propellant 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 – 225 s)	NTP – LH2 (Ispvac = 900 – 1000 s)	RDRE (10% Increase Ispvac)
High Thrust (Pump-Fed)	Large ΔV, Fixed Thrust Surface Ascent			◐		●			
	Large ΔV, Variable Thrust Descent, Hover & Landing			◐ SpaceX Dynetics	● Blue Origin	○ XLR-132/RS-72 Heritage			○ T1-G1
	Limited ΔV, Fixed Thrust In-Space Transfer	●		◐	●	●		○ E3-G2 SNP Program	
Low-to-Moderate Thrust (Pressure-Fed)	Large ΔV, Fixed Thrust Surface Ascent	● Robotic Sample Return	◍			🟡			
	Large ΔV, Variable Thrust Descent, Hover & Landing	●				🟡 Apollo Heritage			
	Reaction/Attitude Control Systems			◍ Nova-C Dynetics	◍ Blue Origin	◐ Heritage	○		
	Limited ΔV, Fixed Thrust In-Space Transfer			E2-G1 Cryogenic Propulsion		◐ S3-G1, S3-G2 Low MON	○ S6-G1		

● Flight System Available

🟡 Flight System Out of Production

◍ Development Underway to meet application requirements

○ Significant Development / Requirements Not Defined

Technology Gap Index

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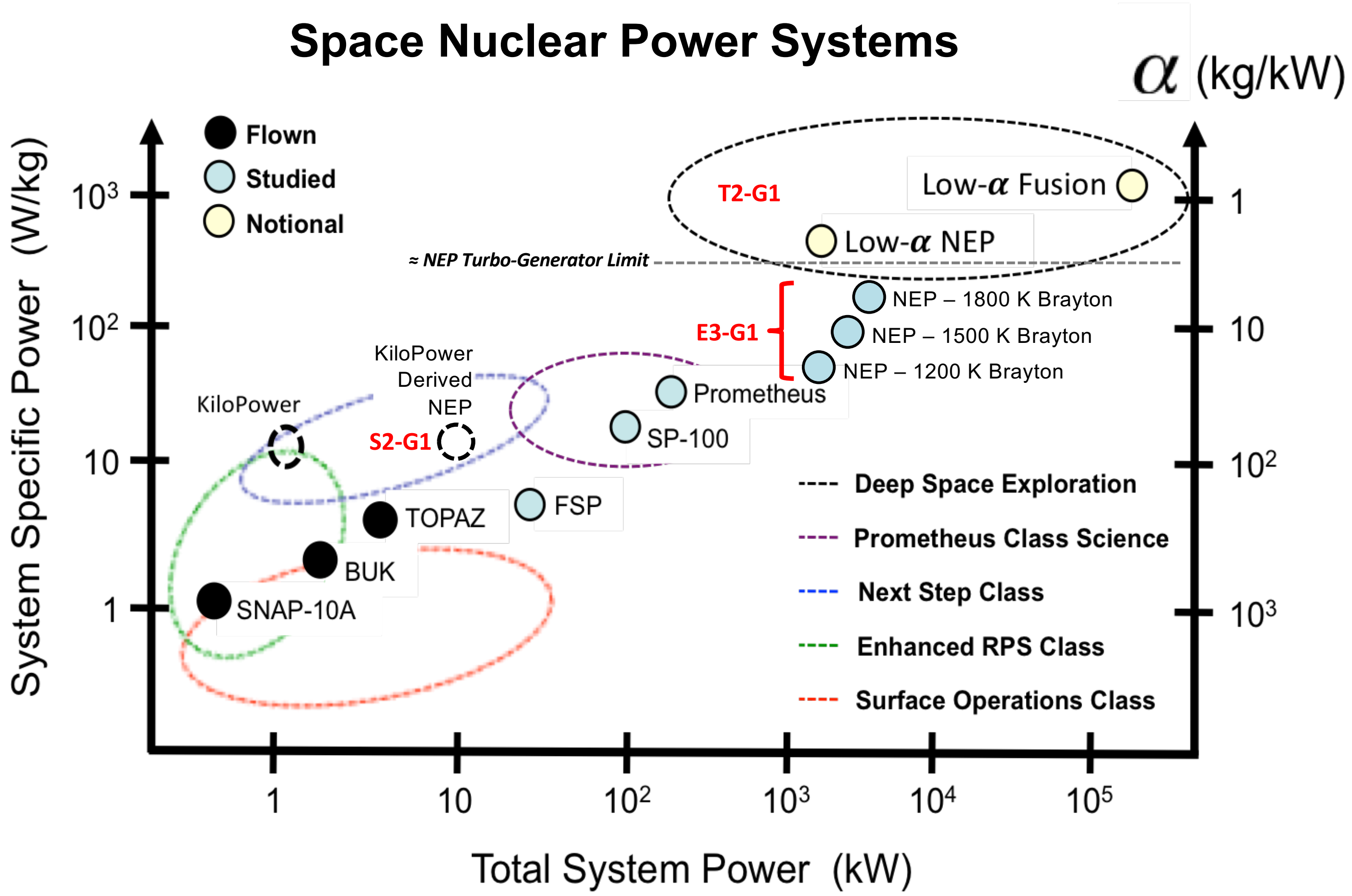
S4-G1	Solar Sail Propulsion
S6-G1	Green Propellant
T1-G1	RDRE

SPACE FISSION POWER SYSTEMS

Historical Developments & Projected Capabilities



Space Nuclear Power Systems

Technology Gap Index

E1-G1	Gateway PPE-SEP
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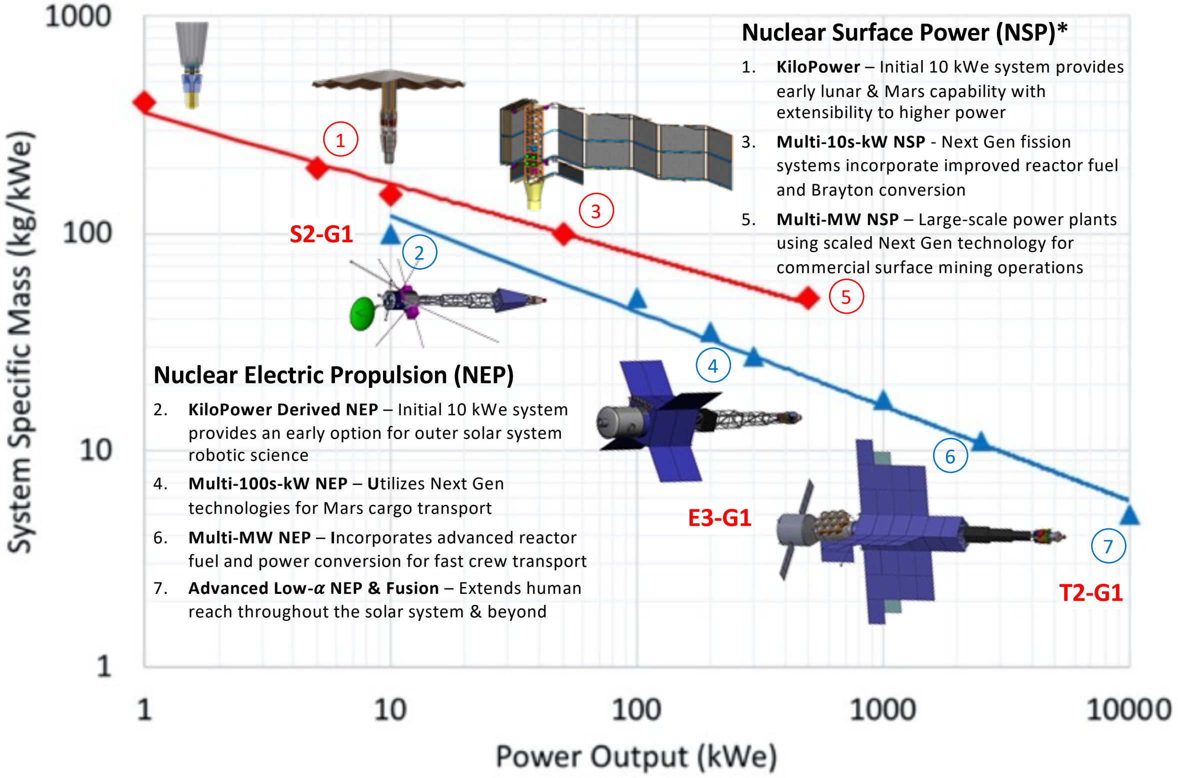
S6-G1	Green Propellant
T2-G1	AEP

SPACE FISSION POWER & PROPULSION SYSTEMS

Synergistic Development of NSP & NEP



Nuclear Surface Power (NSP)*

1. **KiloPower** – Initial 10 kWe system provides early lunar & Mars capability with extensibility to higher power
3. **Multi-10s-kW NSP** - Next Gen fission systems incorporate improved reactor fuel and Brayton conversion
5. **Multi-MW NSP** – Large-scale power plants using scaled Next Gen technology for commercial surface mining operations

Nuclear Electric Propulsion (NEP)

2. **KiloPower Derived NEP** – Initial 10 kWe system provides an early option for outer solar system robotic science
4. **Multi-100s-kW NEP** – **U**tilizes Next Gen technologies for Mars cargo transport
6. **Multi-MW NEP** – **I**ncorporates advanced reactor fuel and power conversion for fast crew transport
7. **Advanced Low-α NEP & Fusion** – Extends human reach throughout the solar system & beyond

Technology Gap Index

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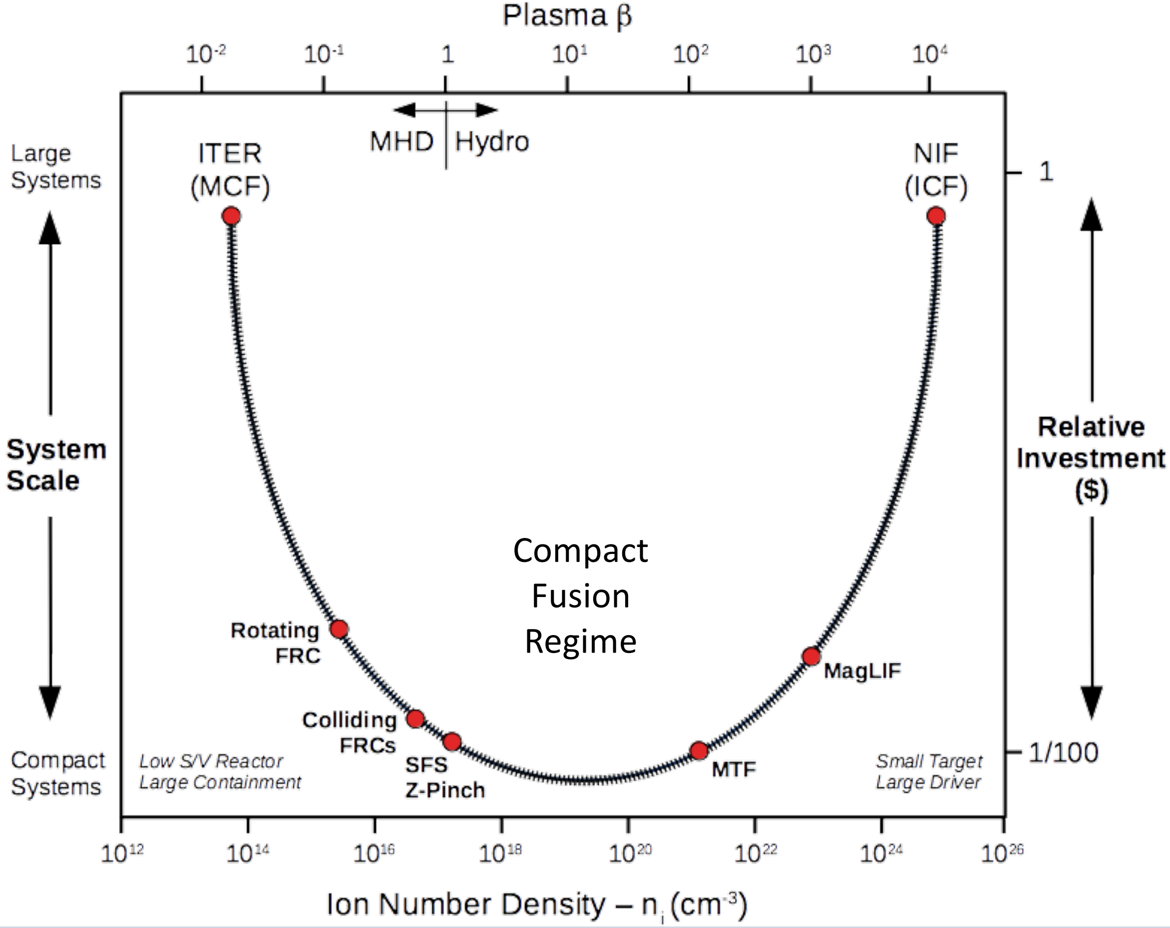
S6-G1	Green Propellant
T2-G1	AEP

***** Apportioned to Advanced Power STP*

COMPACT FUSION TECHNOLOGY DOMAIN

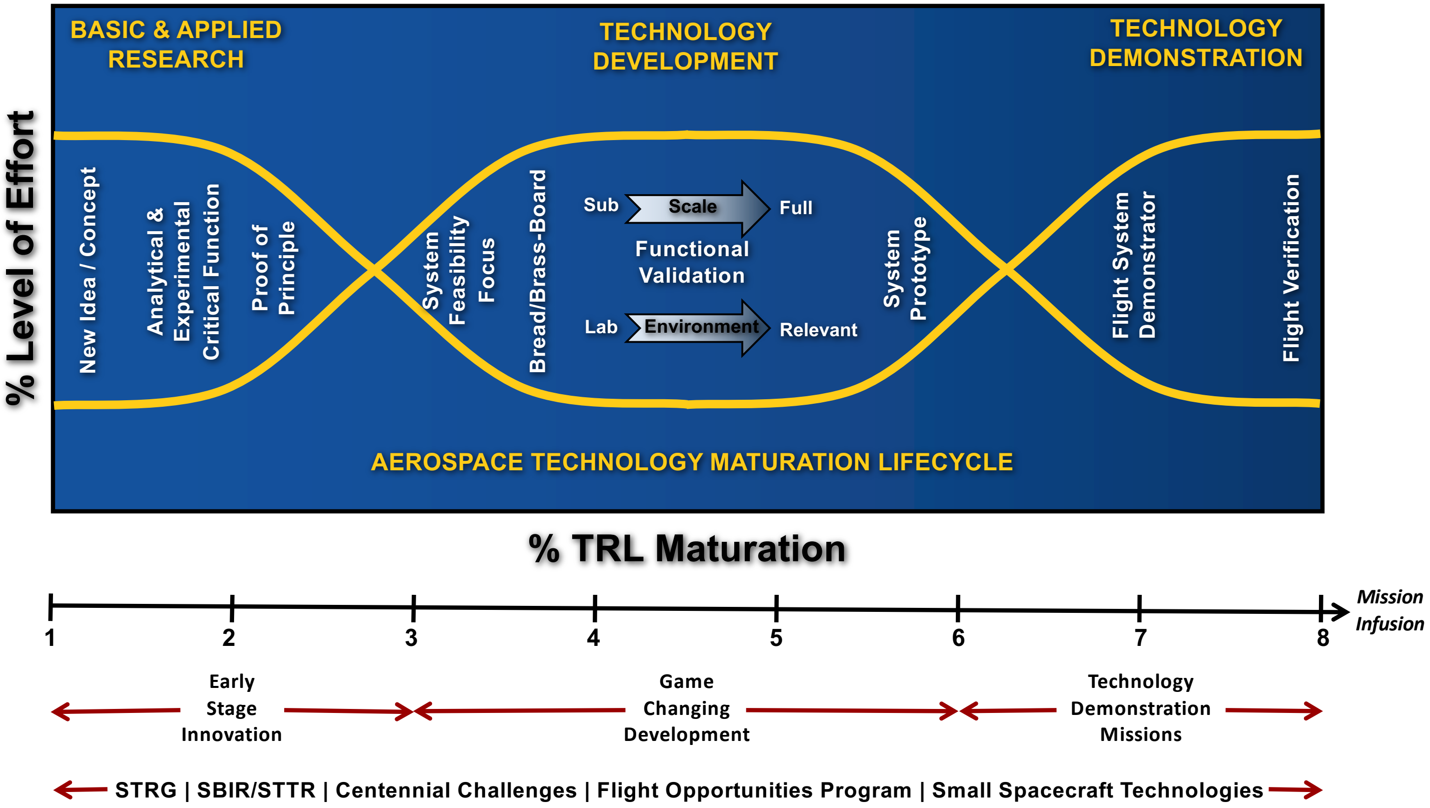
Low-α System Swath Trend



STRATEGIC CROSS-PROGRAM INTEGRATION

STMD Technology Lifecycle

DOUBLE HOURGLASS TRANSITION & INFUSION MODEL



BASIC & APPLIED RESEARCH

TECHNOLOGY DEVELOPMENT

TECHNOLOGY DEMONSTRATION

% Level of Effort

New Idea / Concept

Analytical & Experimental Critical Function

Proof of Principle

System Feasibility Focus

Bread/Brass-Board

Sub → Scale → Full

Functional Validation

Lab → Environment → Relevant

System Prototype

Flight System Demonstrator

Flight Verification

AEROSPACE TECHNOLOGY MATURATION LIFECYCLE

% TRL Maturation

1 2 3 4 5 6 7 8 *Mission Infusion*

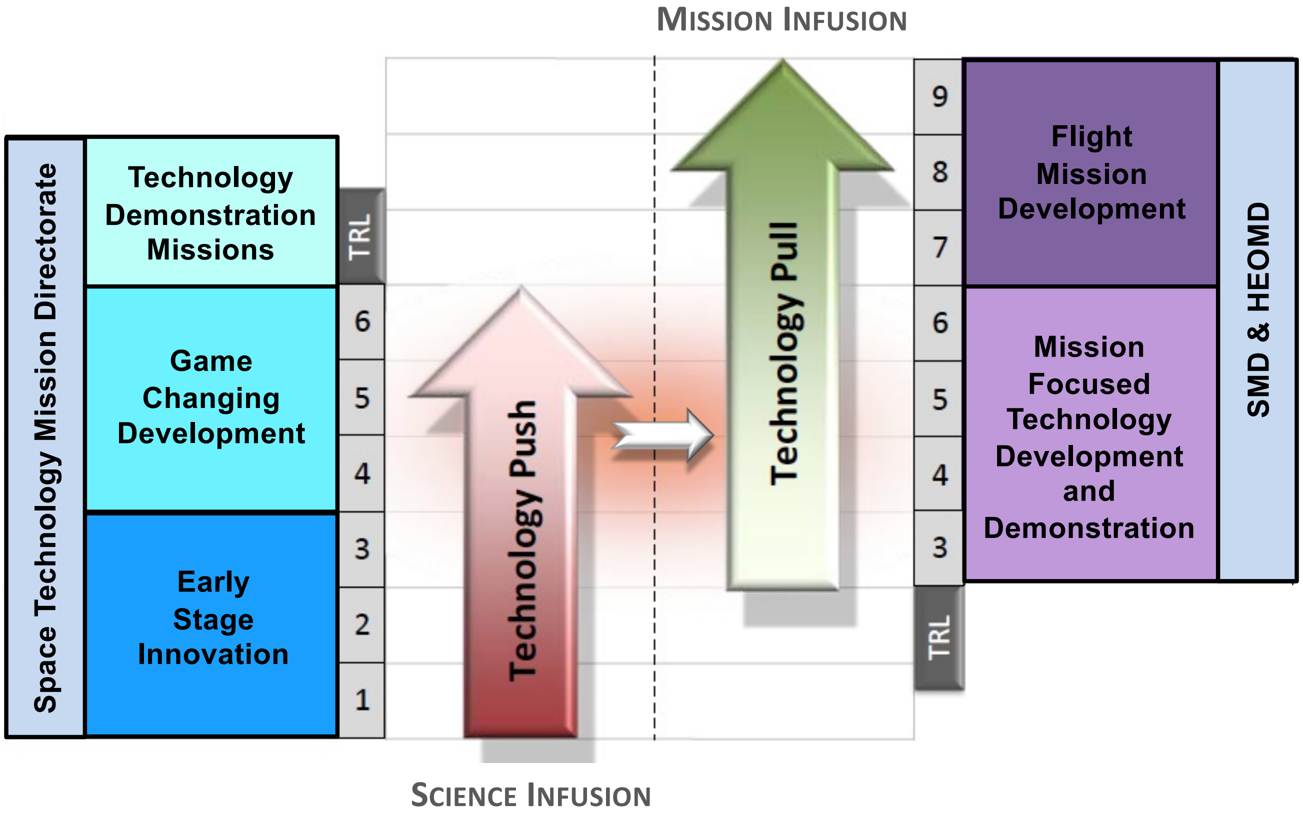
← Early Stage Innovation → ← Game Changing Development → ← Technology Demonstration Missions →

← **STRG | SBIR/STTR | Centennial Challenges | Flight Opportunities Program | Small Spacecraft Technologies** →

SPACE TECHNOLOGY MISSION DIRECTORATE PROGRAM PORTFOLIO

STRATEGIC CROSS-PROGRAM INTEGRATION

Space Technology Programmatic Flow



MISSION INFUSION

Space Technology Mission Directorate

Technology Demonstration Missions

Game Changing Development

Early Stage Innovation

TRL 1 2 3 4 5 6

Technology Push

Technology Pull

TRL 3 4 5 6 7 8 9

Flight Mission Development

Mission Focused Technology Development and Demonstration

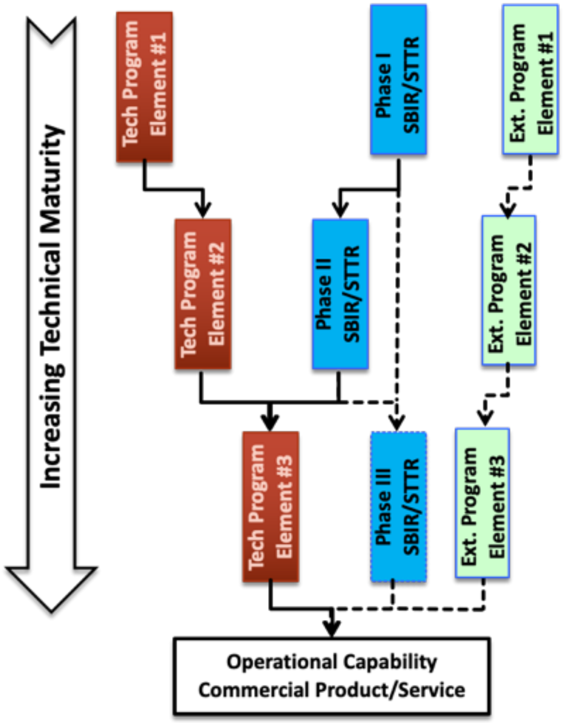
SMD & HEOMD

SCIENCE INFUSION

STRATEGIC CROSS-PROGRAM INTEGRATION

Integrated Program Elements

INTEGRATED PROGRAM ELEMENTS



Increasing Technical Maturity

Tech Program Element #1

Phase I SBIR/STTR

Ext. Program Element #1

Tech Program Element #2

Phase II SBIR/STTR

Ext. Program Element #2

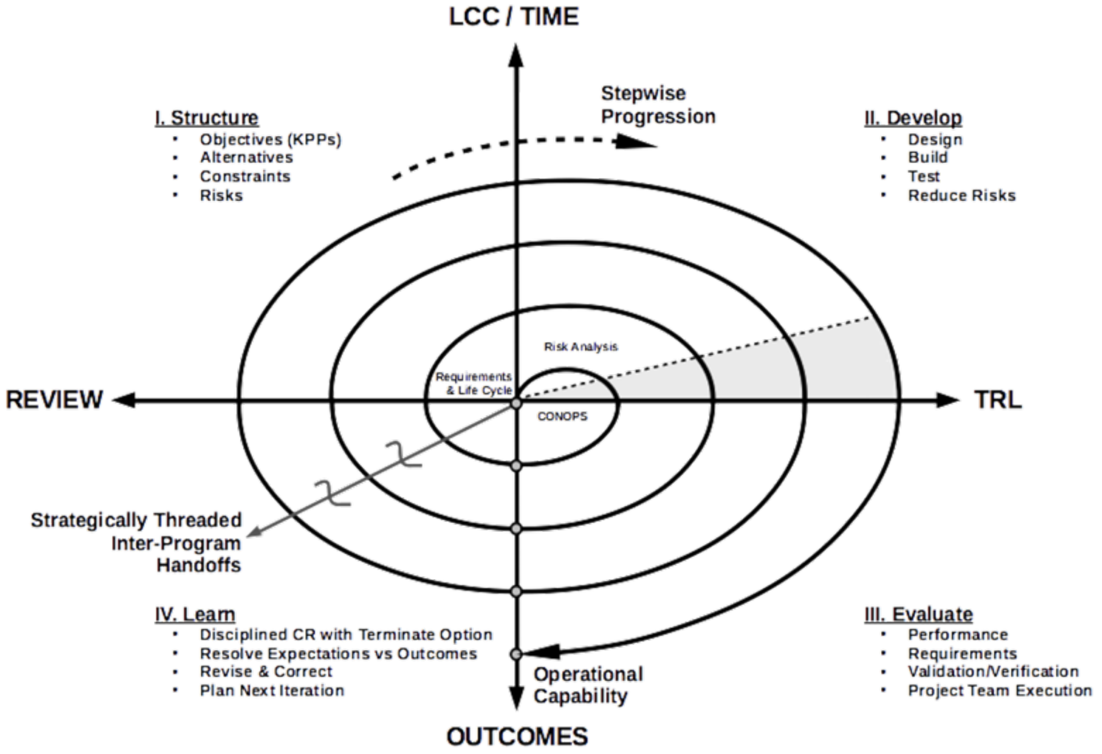
Tech Program Element #3

Phase III SBIR/STTR

Ext. Program Element #3

Operational Capability
Commercial Product/Service

CAPABILITY DEVELOPMENT COMMITMENT PARTITION



LCC / TIME

I. Structure
- Objectives (KPPs)
- Alternatives
- Constraints
- Risks

Stepwise Progression

II. Develop
- Design
- Build
- Test
- Reduce Risks

Risk Analysis

Requirements & Life Cycle

CONOPS

REVIEW

TRL

Strategically Threaded Inter-Program Handoffs

IV. Learn
- Disciplined CR with Terminate Option
- Resolve Expectations vs Outcomes
- Revise & Correct
- Plan Next Iteration

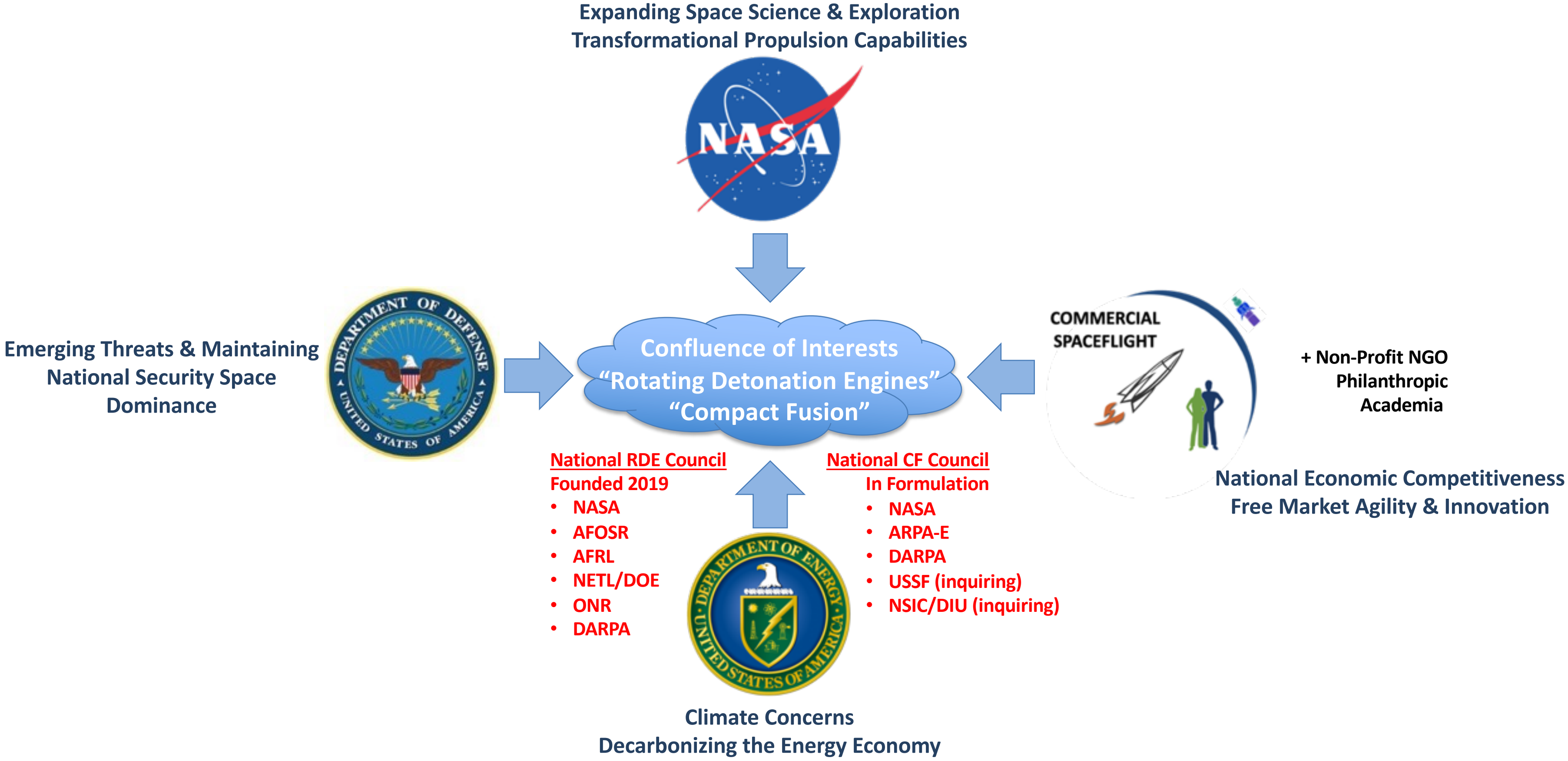
Operational Capability

III. Evaluate
- Performance
- Requirements
- Validation/Verification
- Project Team Execution

OUTCOMES

INTER-AGENCY WHOLE OF GOVERNMENT MINDSET

A National Imperative



Expanding Space Science & Exploration
Transformational Propulsion Capabilities

Emerging Threats & Maintaining National Security Space Dominance

Confluence of Interests
“Rotating Detonation Engines”
“Compact Fusion”

+ Non-Profit NGO
Philanthropic
Academia

National Economic Competitiveness
Free Market Agility & Innovation

National RDE Council
Founded 2019
- NASA
- AFOSR
- AFRL
- NETL/DOE
- ONR
- DARPA

National CF Council
In Formulation
- NASA
- ARPA-E
- DARPA
- USSF (inquiring)
- NSIC/DIU (inquiring)

Climate Concerns
Decarbonizing the Energy Economy

NASA