National Aeronautics and
Space Administration

Space Technology Mission Directorate

SPACE LIFE & PHYSICAL SCIENCES SYMPOSIUM

Physical Processes & Technologies for Exploration

Plans and Design Challenges for Nuclear Thermal Propulsion Systems Supporting Deep Space Transportation

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Principal Technologist for Propulsion
NASA/STMD | HQ

28 March 2018

LONG RANGE SPACE FLIGHT GOALS

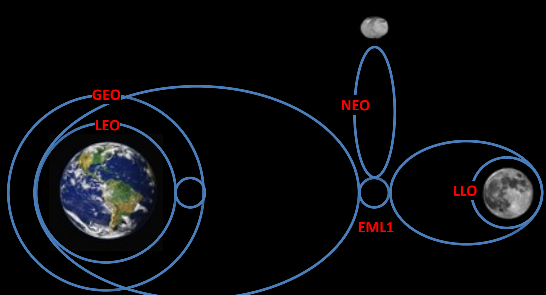
A Public-Private-International Collaboration

Space Flight Goals

Commercially Driven Cis-Lunar Development

- Science Payloads
- Mining & Resource Extraction
- Manufacturing
- Fuel Depots
- Space Solar Power Harvesting
- Human Outposts (In-Space & Surface)
- Tourism

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



Chemical | SEP | NTP | NEP

EXPANDING SCIENCE/EXPLORATION

Mars
1.5 au
$\Delta v \approx 10$ km/s

Jupiter
5.2 au
$\Delta v \approx 30$ km/s

Saturn
9.5 au
$\Delta v \approx 60$ km/s

Uranus
19 au
$\Delta v \approx 120$ km/s

Neptune
30 au
$\Delta v \approx 200$ km/s

Advanced Energetic Propulsion Processes & Concepts

Interstellar Precursors & Probes

2018 BUDGET ACT EXCERPT
SPACE TECHNOLOGY
This Act includes $760,000,000 for Space Technology. Within this amount, $130,000,000 is for RESTORE; $75,000,000 is for nuclear thermal propulsion activities; up to $20,000,000 is for the Flight Opportunities Program; and no less than $25,000,000 is for additive manufacturing research.

Deep Space Technical Challenges

- In-Space Propulsion & Power
- Habitats & Life Support Systems
- Crew Health – Radiation & Zero-G Effects

ER&T TRANSPORTATION CAPABILITY STRATEGY

System Drivers & Diversification

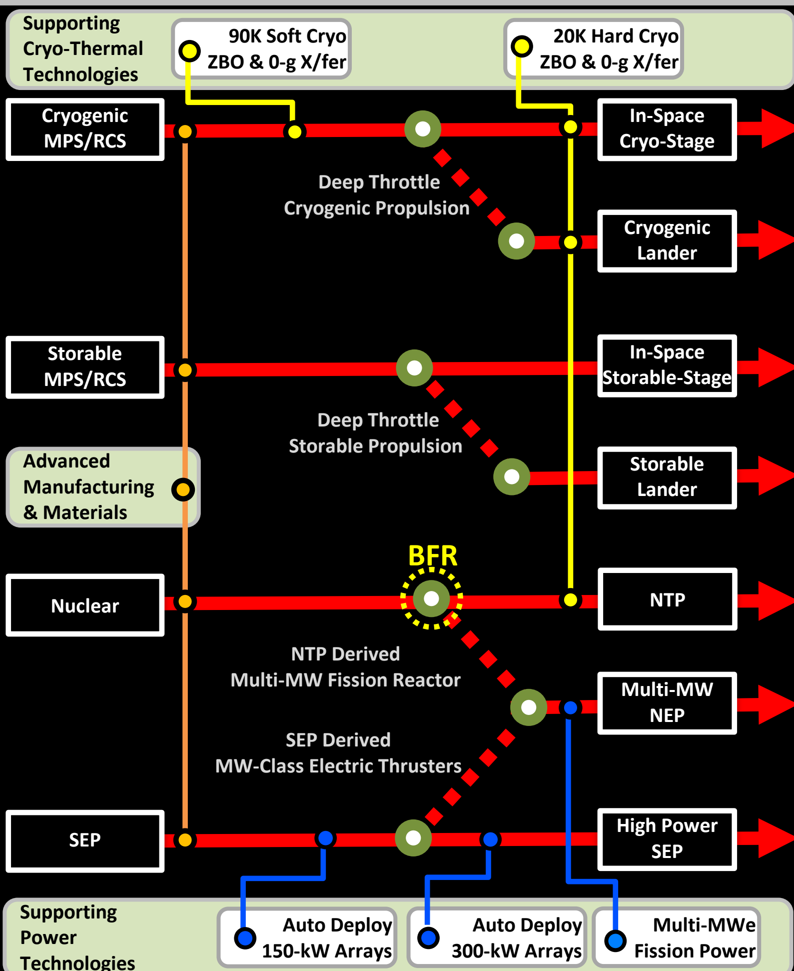
Exploration Systems
Cis-Lunar/Mars

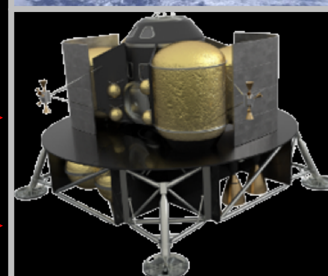
Very Rapid Transit

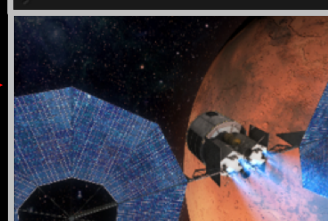
Interstellar Precursors & Interstellar Probes

TRANSPORTATION TECHNOLOGIES

SYSTEMS



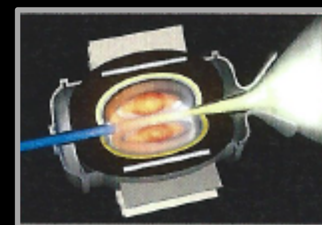




BREAKTHROUGH PROPULSION CONCEPTS

Sustained research investment enables possibility for new breakthrough technologies – PROGRESS IS NOT PREDICTABLE

Low-α NEP



Fission Gas Core or Enhanced Solid Core

Pulsed Fission

Directed Energy & Sails

Pulsed Fusion

Antimatter

Breakthrough Science

Sustained Research on Breakthrough Propulsion Concepts

Multi-MW Low-α NEP, Directed Energy, Advanced Fission, Fusion, Antimatter, etc.

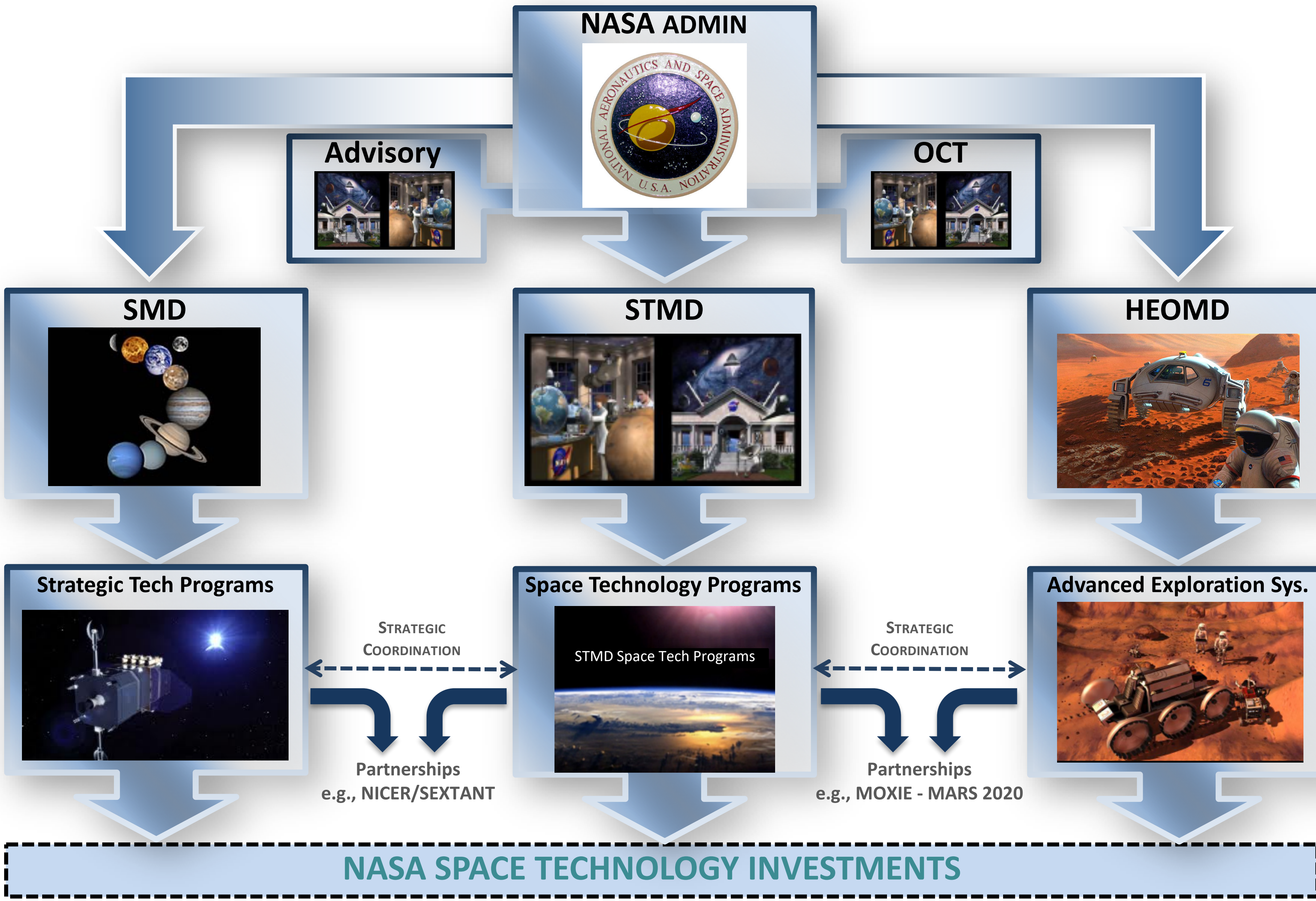
Key Challenges:
- Complex & Costly
- Long Learning Curves
- High Failure Rates

Tangible Action to Remove "Barriers to Innovation"

Capability Goals:
- $\alpha \leq 5$ kg/kW
- Acceleration $\geq$ 0.6 mm/sec^2 @ 1 au
- Relativistic S/C Velocity $\geq$ 0.1c

NASA SPACE TECHNOLOGY TODAY

Multi-Mission Directorate Technology Structure

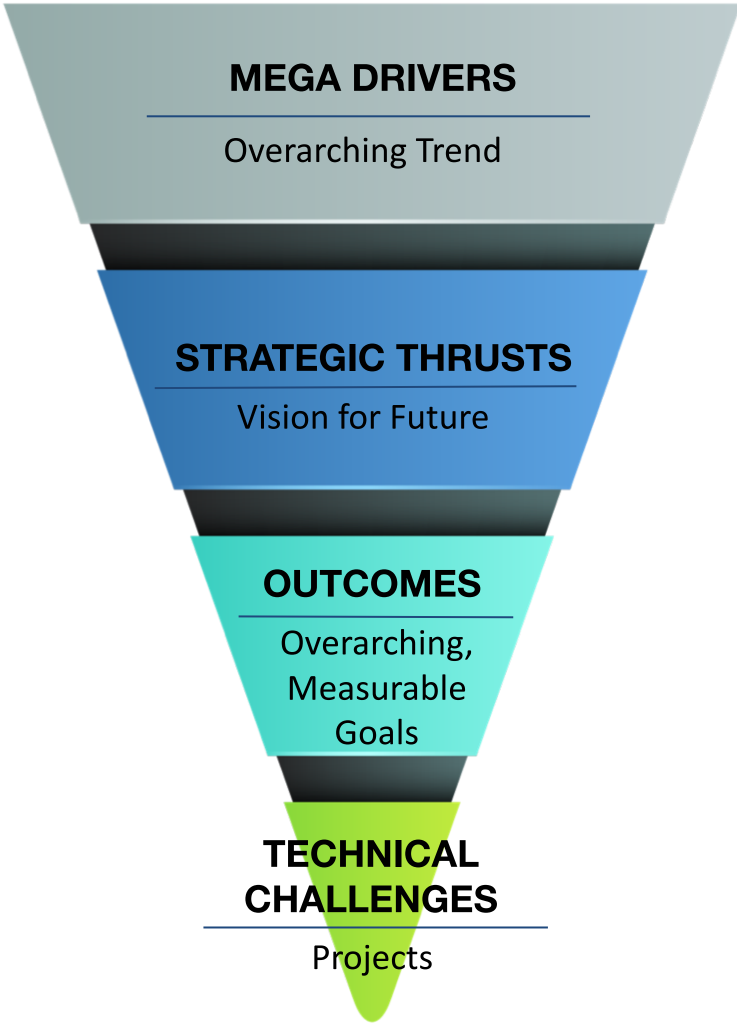


NASA SPACE TECHNOLOGY TOMORROW

Unified Exploration Research & Technology Structure

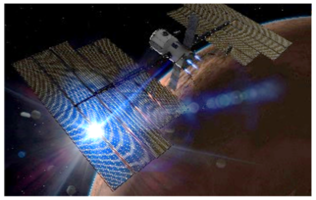
STMD & AES Merging into an Exploration Research & Technology Organization

Strategic Framework

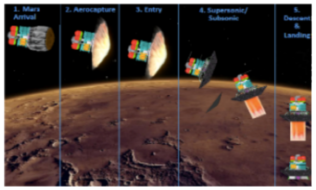


Strategic Thrusts

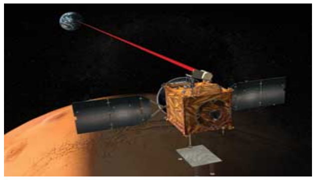
ST1. Accelerate the Industrialization of Space



ST2. Enable Safe and Efficient Transportation Into and Through Space



ST3. Increase Access to Planetary Surfaces



ST4. Expand Capabilities through Robotic Exploration and Discovery

ST5. Enable Humans to Live and Work in Space and on Planetary Surfaces

ST6. Grow and Utilize the U.S. Industrial and Academic Base

PROPULSION CAPABILITY OBJECTIVES

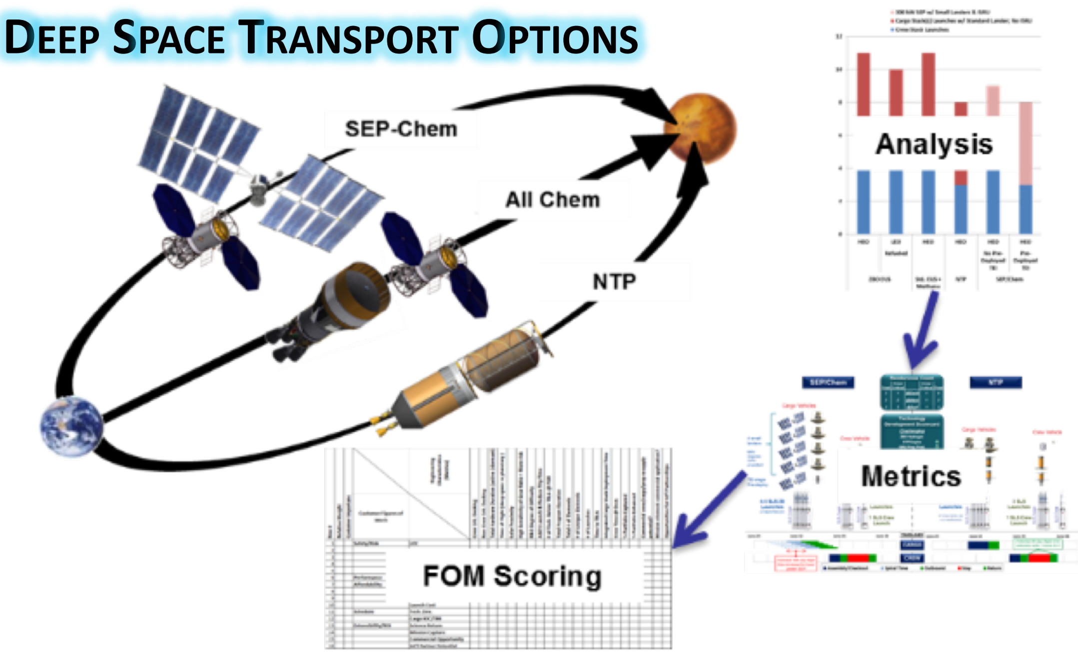
Quantifiable Capability Mapping to ER&T

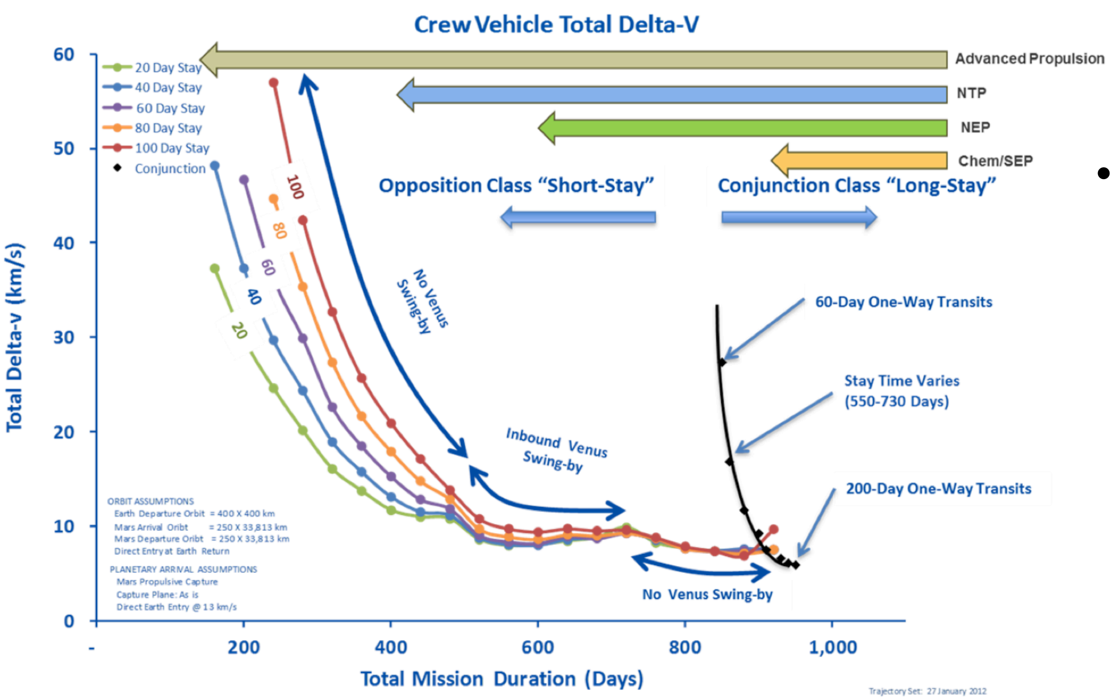
Capability Objective	Quantifiable Metrics	ER&T
High-Power EP *– Highly Efficient Transit –*	• HERMES – 12.5 kW Magnetically Shielded Hall Effect Thruster • HERMES' – 30-50 kW Magnetically Shielded Hall Effect Thruster • Evolve Multi-String SEP Systems to 300-kW • Long Life Durability enabling High-Delta-V & Mission Utilization > 1 • Advanced Scale-Up: Very High Power EP – 0.1-1 MW Thruster Systems	ST2 High Priority
NTP *– Rapid Transit –*	• Thrust ≥ 25klbf @ Thrust/Weight ≥ 3 • High Temperature Fuel Element Temp ≥ 2850 K @ Isp ≥ 850 sec • ΔV ≥ 10 km/s – Enable Opposition & Conjunction EMC Mission Options • Fission Product Leakage << NERVA/ROVER Milestone • Run Duration ≥ 2 hrs @ rated temperature • Engine Restarts ≥ 10 • Hydrogen CFM - Zero Boil Off & Liquefaction at Low Power (kW's @ 20k) • NTP Engine System Development LCC ≈ Comparable Scale LRE LCC ($1-2B)	ST2 High Priority
In-Space Cryogenic Propulsion *– Transport & Landers/Ascent –*	• MPS Thrust 5 - 25 klbf with 5:1 Throttling Capability • RCS Thrust ≥ 100 lbf with Integrated Feed Systems • Isp > 360 sec • Lifetime > 300 hours • LOX/Methane CFM - Zero Boil Off and Liquefaction at Low Power (100's Watts @ 90K)	ST2/ST3 High Priority
In-Space Storable Propulsion *– Transport & Landers/Ascent –*	• 100-lbf Class MON-25/MMH Bipropellant Engine (Flight Qualified within 2 years) • Reduce Propellant Freezing Point < -40 °C • Reduce Propulsion System Mass ≥ 80% • Reduce Propulsion System Volume ≥ 50% • Reduce Propulsion System Cost ≥ 60% • Exploration Scale-Up: RCS Thrust = 100-1000 lbf | MPS Thrust = 25,000 lbf	ST2/ST3 Low Priority (Phase Out)
Small Spacecraft Launch & Small Spacecraft Technology *– Commercial & Exploration Applications –*	• 5-180 kg payload delivery capacity to 350-700 km (CONUS & Sun Synchronous Ops) • Launch Costs < $60,000/kg; m_p ≥ 50kg • Launch Costs < $3M/Launch; m_p < 50kg • Small S/C Sub-KW EP: ΔV > 5km/s @ <1-kW with 7x Increase in Propellant Throughput	ST2 Reduced Priority (Realign)
In-Space Green Propulsion *– Transport & Landers/Ascent –*	• Scale-Up: 22-N Green Monopropellant Thruster (Flight Qualified within 3-5 years) • Scale-Up: 110-N Thruster (5-7 years), 440-N Thruster (7-10 years) • Increase Density-Isp ≥ 25% • Reduce Propellant Freezing Point < -40 °C • Reduce Thruster Power Consumption ≥ 50% • Increase Propellant Throughput/Lifetime ≥ 125 kg • Reduce Ground Operation Costs ≥ 50% (Reduce or Eliminate SCAPE Suit Ops)	ST2/ST3 Low Priority (Phase Out)
Breakthrough In-Space Propulsion *– Very Rapid Transit –*	• Ultra Low Propulsion System Specific Mass: $\alpha \leq 5$kg/kW • High Characteristic Acceleration at 1 AU: $a \geq 0.6$ mm/sec^2 • Enable Relativistic Spacecraft Velocity: $v > 0.1c$	ST2 High Priority

NTP ARCHITECTURAL ROBUSTNESS

Why NTP?

DEEP SPACE TRANSPORT OPTIONS



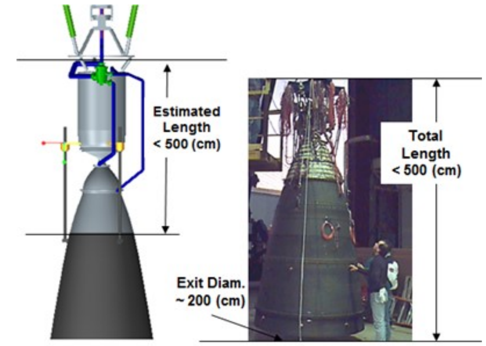


- **NTP Enhances Architectural Robustness**
  - NTP = **high thrust** + **high Isp** (≈ 900s)
  - Chem = **high thrust** + **low Isp** (<460s)
  - SEP = **very low thrust** + **very high Isp** (≈3000s)
- **NTP Robustness is Highly Enabling**
  - Rapid transits & reduced mission duration
  - Reduces GCR dose & zero-g health impacts
  - Reduces launch up-mass & lowers launch count
  - Reduces mission cost
  - Increases mission payload
  - Enables off nominal mission opportunities
  - Enables mission abort scenarios
- **NTP is a Space Nuclear Technology Trailblazer**
  - Engender acceptance of space nuclear systems
  - Enable vigorous deep space exploration & science
  - Lead to new Breakthrough Propulsion Technology

BASELINE NTP ENGINE SYSTEM

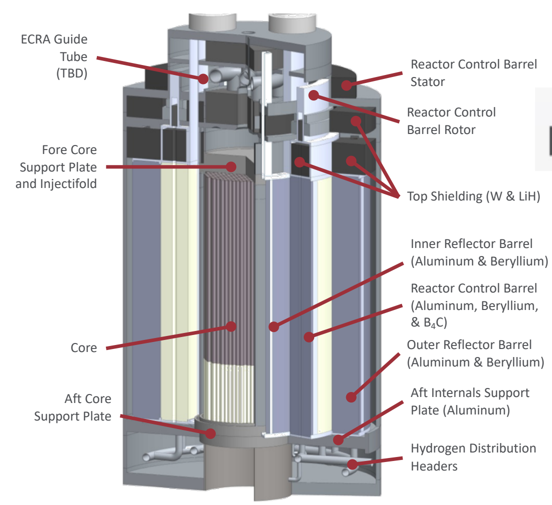
Engine & Reactor Requirements

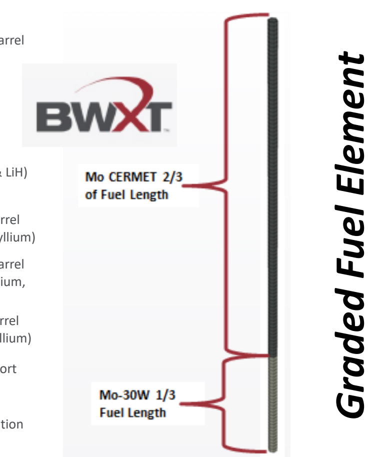
- **Baseline Low Enriched Uranium (LEU) NTP Requirements**
  - ▹ Utilization of LEU Addresses Cost/Proliferation/Security Issues
  - ▹ 25,000-lbf thrust | T/W > 3
  - ▹ Isp > 850s
  - ▹ ≈ 500-MWth reactor
  - ▹ ≈ 1hr total burn time



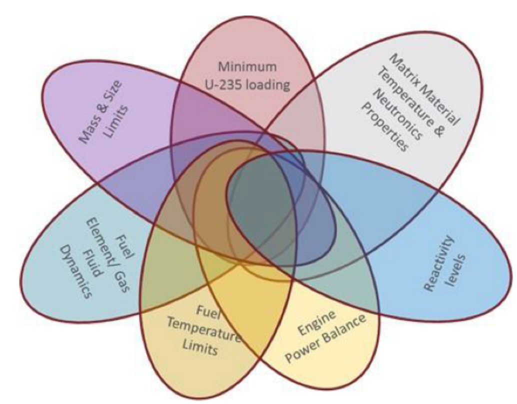
Size Comparison: Baseline 25klbf NTP (left) vs. RL10 (right)

- **NTP Reactor Design Features - BWXT**
  - ▹ CERMET fuel
  - ▹ Graded Mo-to-Mo/W fuel element
    - – Reduces engine mass & need for purified W-184
  - ▹ UO_2 vs UN (High Assay LEU – HALEU)
    - – UO_2: Small window of feasibility
    - – UN: Feasible design space with strong moderation & natural Mo
      - » Increase in U-235 loading opens design space
      - » Neutronic & thermal design requirements more easily met
      - » Ability to use wider variety of matrix materials
  - ▹ Multiple CERMET fuel element fabrication options



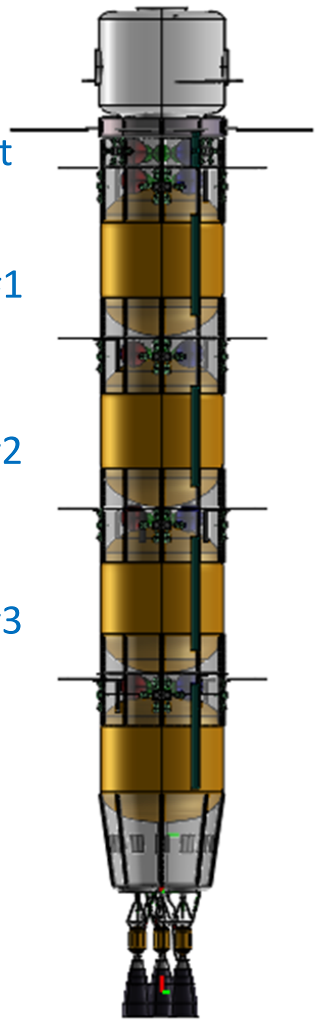


Fuel	Advantages	Disadvantages
UO_2	• Well characterized • Easy to manufacture	• Lower specific uranium content (compared to UN) • Decomposes at high temperature • Requires stabilization to maintain stoichiometry • Low thermal conductivity • CTE large at high temperature
UN	• ~40% greater specific uranium content • ~10 times higher thermal conductivity at temperature • CTE low at high temperature	• Not as well characterized as UO_2 • Difficult to manufacture – must keep O_2 out • Dissociates into free uranium and nitrogen at > 1770 K • Requires back pressure with N_2 to prevent dissociation

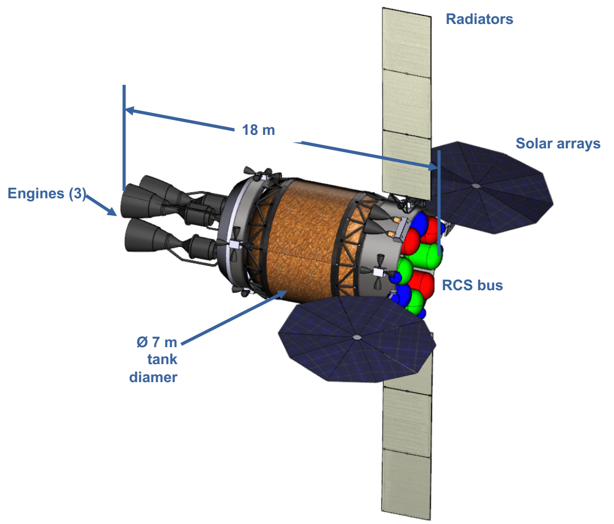


NTP DEEP SPACE TRANPORT

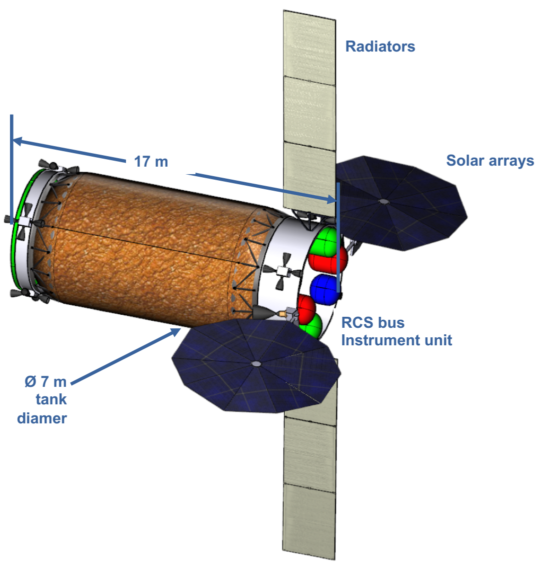
Baseline Configuration



Deep Space Transport Stack

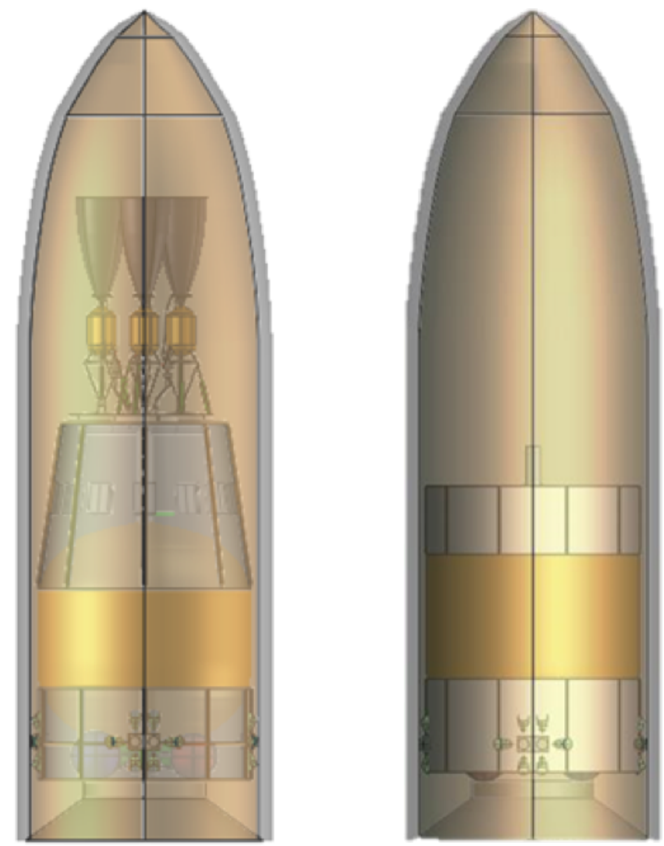


Core Stage



In-Line Stage

	Core Stage	Inline Stages #1-3
Tank Diameter (m)	7.0	7.0
Stage Length (m)	19.2	11.1
Gross Mass (mT)	43.9	43.9



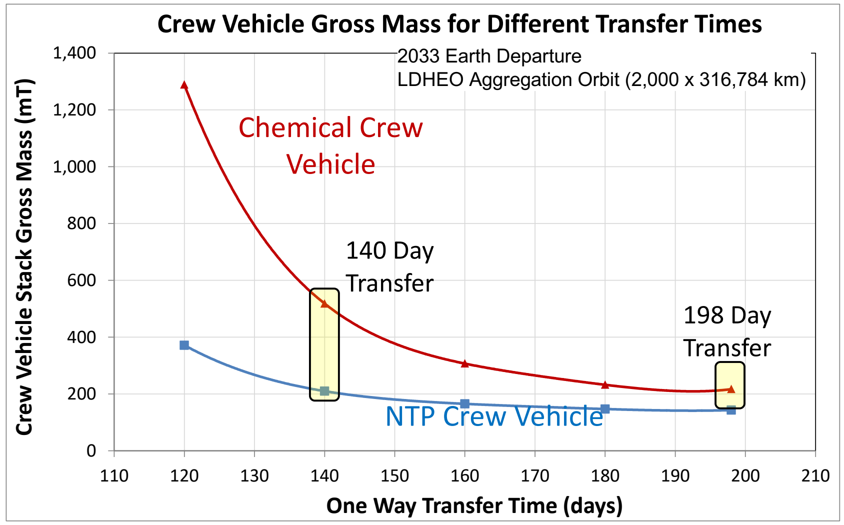
Core Stage In-line Stages #1-3

SLS Launch Configuration

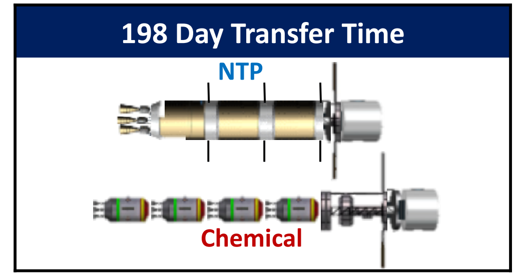
NTP ARCHITECTURAL ROBUSTNESS

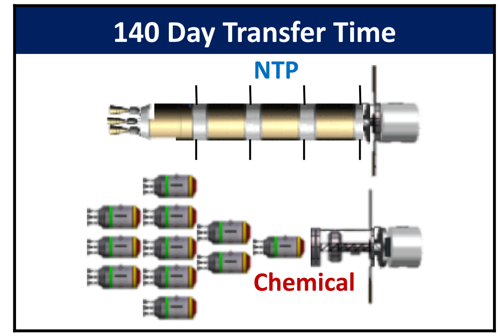
Mars Exploration Benefits

RAPID TRANSIT VS ENHANCED PAYLOAD

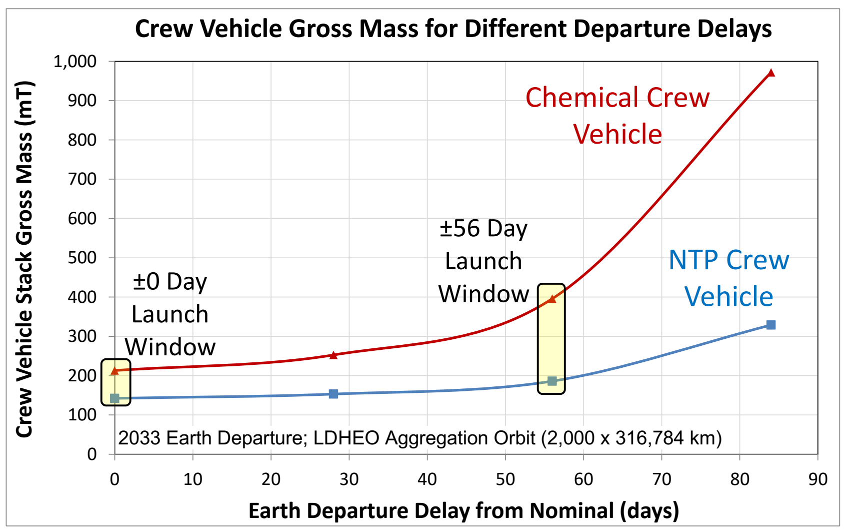


NTP Mars Crew Vehicle 34-71% Lighter than Chemical Vehicle For the Same Transfer Time

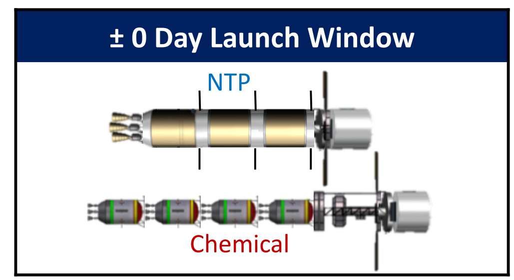


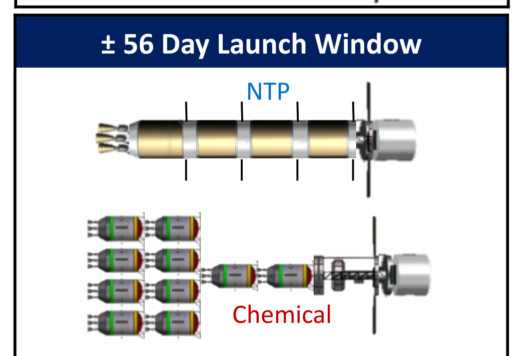


WIDER OFF NOMINAL LAUNCH WINDOWS



NTP Mars Crew Vehicle 33-66% Lighter than Chemical Vehicle For the Same Launch Window



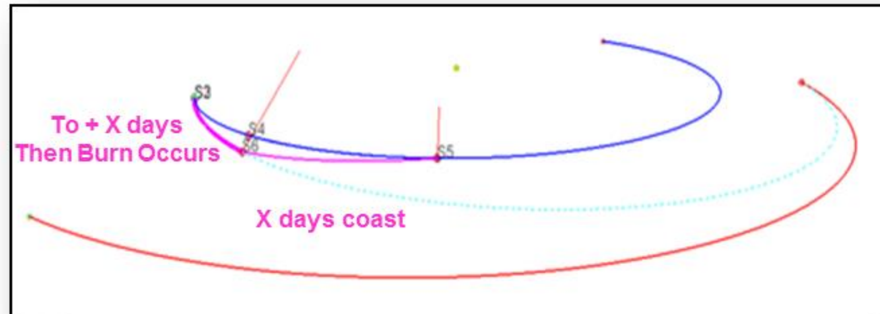


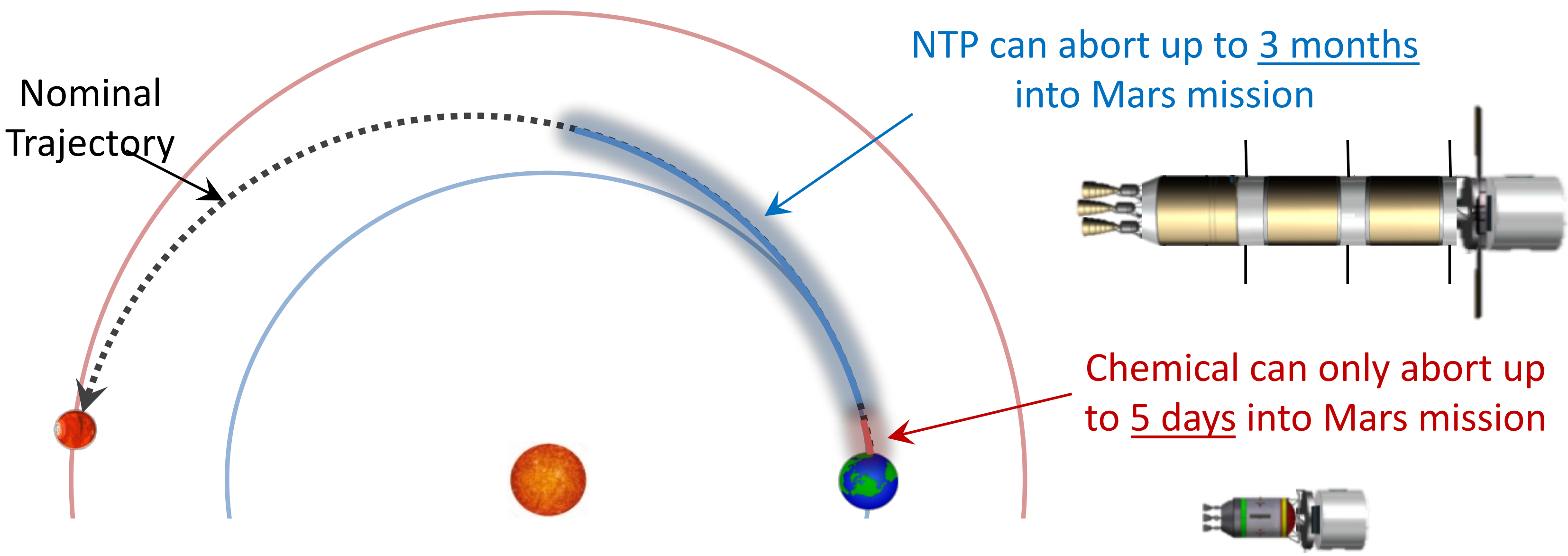
NTP ARCHITECTURAL ROBUSTNESS
Mars Exploration Benefits

Robust Abort Scenarios

- **NTP Crew Vehicle carries all the mission propellant it needs if abort is required after Earth departure**
- **LOX/CH4 Chemical Crew Vehicle has minimal abort capability due to need to pre-position return propellant**

Copernicus Trajectory Analysis



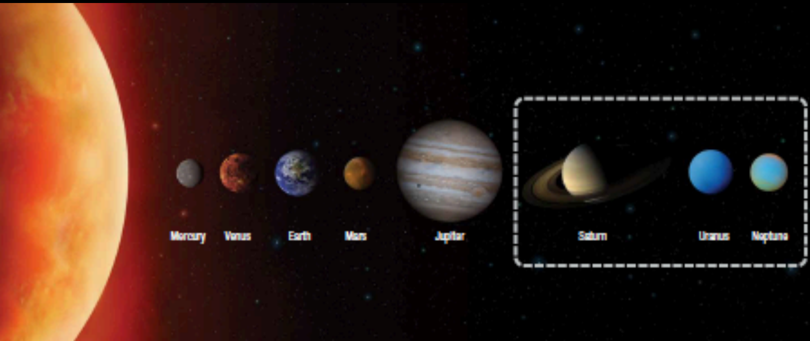


Based on Analysis of EMC 2033-2048 Missions

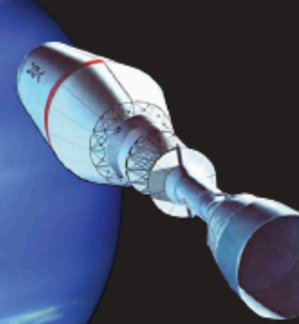
NTP has Robust In-Space Abort Capability – Chemical has Minimal Capability

NTP ARCHITECTURAL ROBUSTNESS

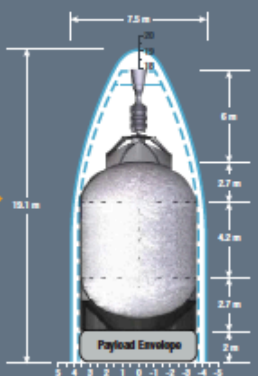
Outer Solar System Science Mission Benefits



- Imagine Cassini class missions to the outer solar system
- Curiosity class rover possible on Triton
- Shortened trip times
- NTP enables approximately 5X the payload capability to the outer planets than SLS only or SLS with solid motor upperstage
- No gravity assist required
- Allows orbit capture in the outer solar system



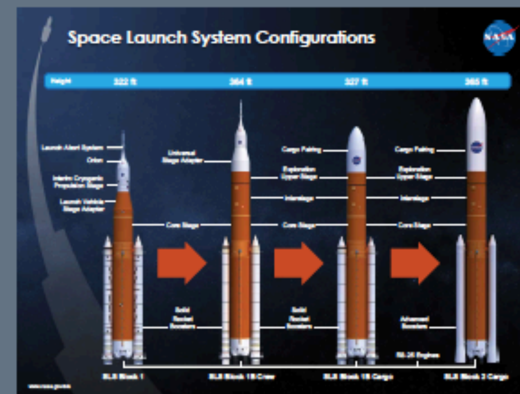
How Best to Use NTP

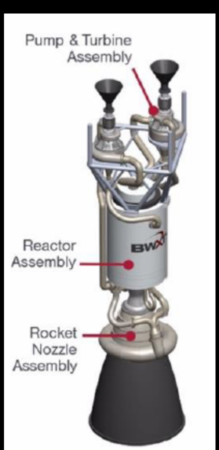


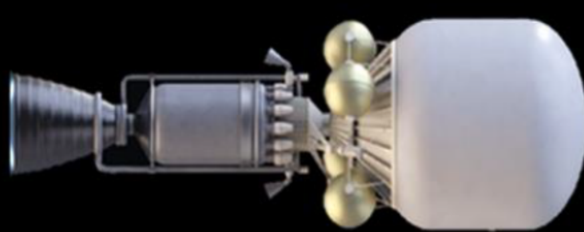
Configuration – SLS 1B (8.4-m fairing)

Ground Rules & Assumptions

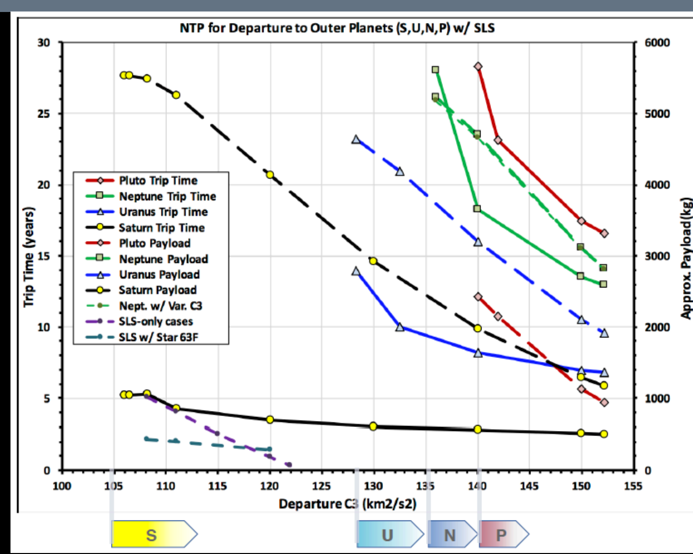
- Direct flight to target planets
- NTP engine (3.5 mT engine mass, 850 sec Isp, 25,000 lbf thrust, LH_2 propellant)
- All Earth Departures take place from a C3 = –10 km^2/s^2
- SLS to C3 = –10 km^2/s^2: 42.8 mt
- Length in 62.7ft SLS fairing for S/C: 17.8 m
- Falcon Heavy to C3 = –10 km^2/s^2: 15 mt
- Length in 13.1m FH fairing for S/C: <13 m
- NTP is dropped off after departure burn
- Captures at outer planets are into elliptical orbits with apoapses at moons' distances
- Capture is done with storable prop (Isp = 320 sec)
- SLS + SRM comparison case done with a STAR 63F-derived motor (Isp = 295 sec)







Single NTP Engine Robotic Science Stage



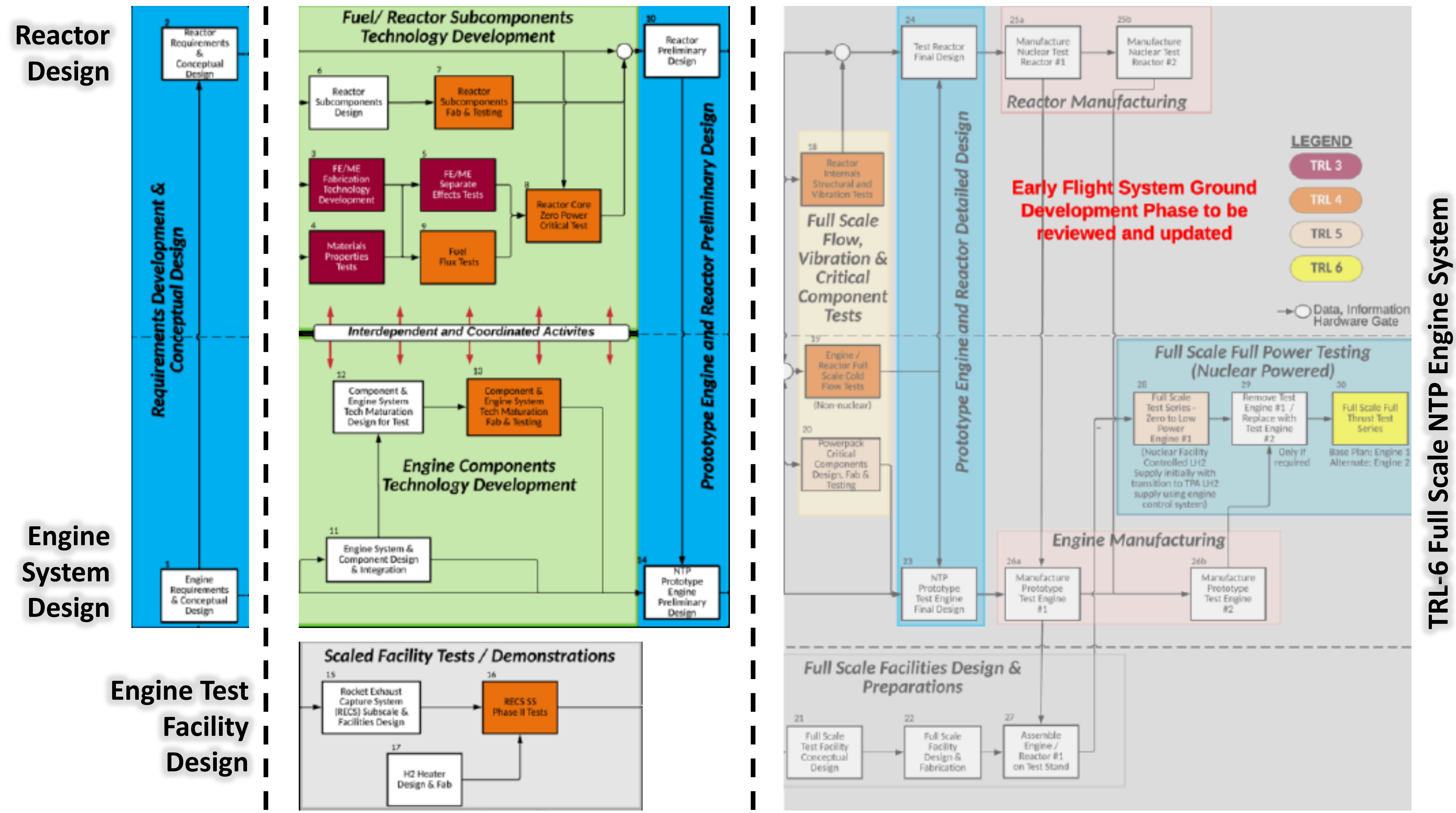
NTP CAPABILITY DEVELOPMENT STRATEGY

Technology Maturation & Systems Dev Plan

GAME CHANGING DEVELOPMENT PROGRAM
NTP Technology Maturation
(≈$50M / FY16-FY19)

TECHNOLOGY DEMONSTRATION PROGRAM
NTP Technology Ground Development
(≈$250-300M / FY18-FY21)

EXPLORATION SYSTEMS DEVELOPMENT PROGRAM
NTP Engine System Development
(> FY21)



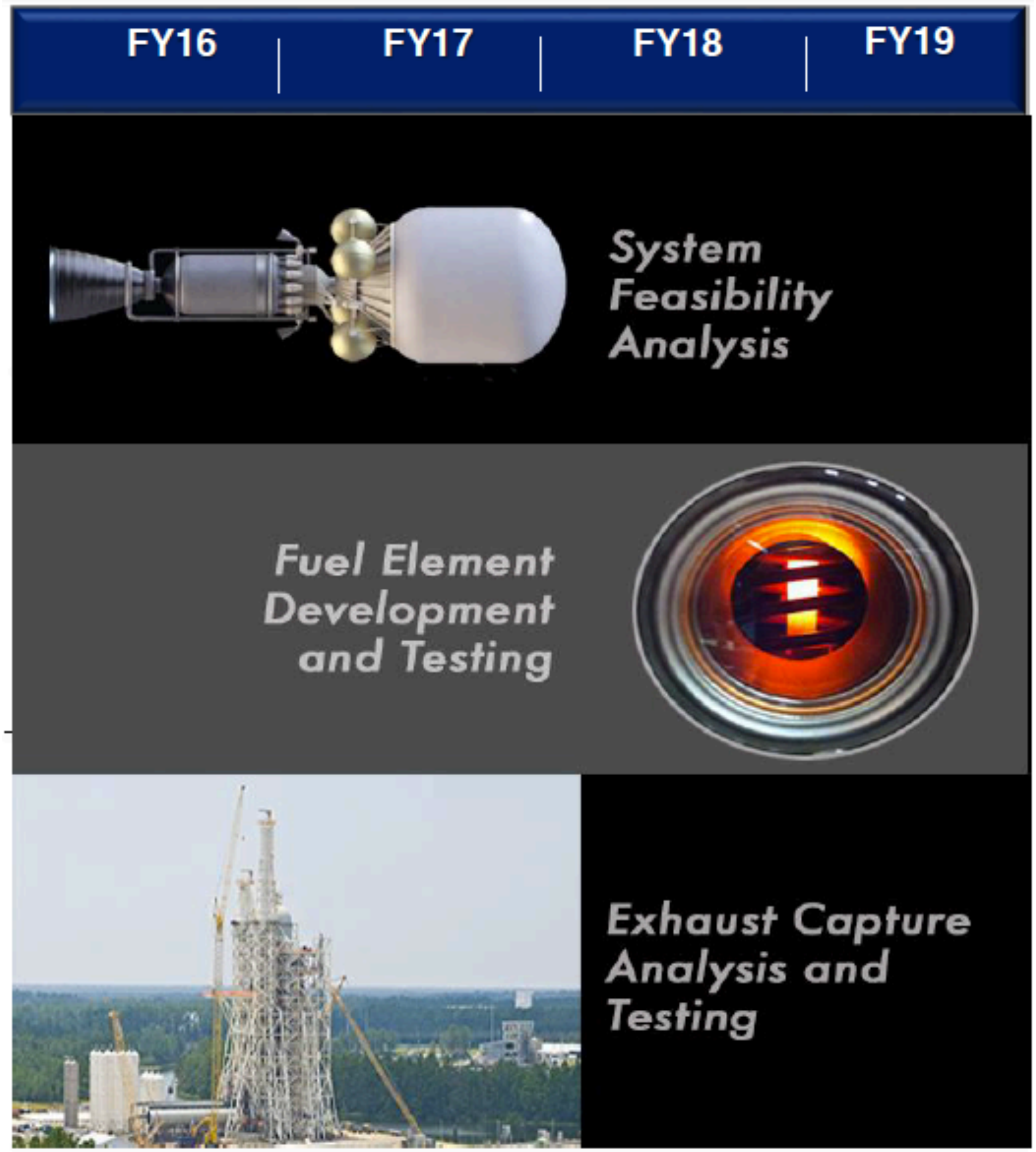
NTP CAPABILITY DEVELOPMENT STRATEGY

GCD Program Technology Maturation

GAME CHANGING DEVELOPMENT PROGRAM

NTP Technology Maturation

The overall goal of the GCD project is to determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence



Task Descriptions:

- **Reactor**
  - Establish design requirements
  - Develop conceptual design
- **Engine System**
  - Establish design requirements
  - Develop conceptual design
- **Test Facility**
  - Trade Studies
  - Sub-scale Demonstration

TECHNOLOGY DEMONSTRATION PROGRAM

NTP Ground Development Testing of Reactor Component Design, Fabrication, & Application of Technology

Zero Power Critical Assembly Facilities | TREAT

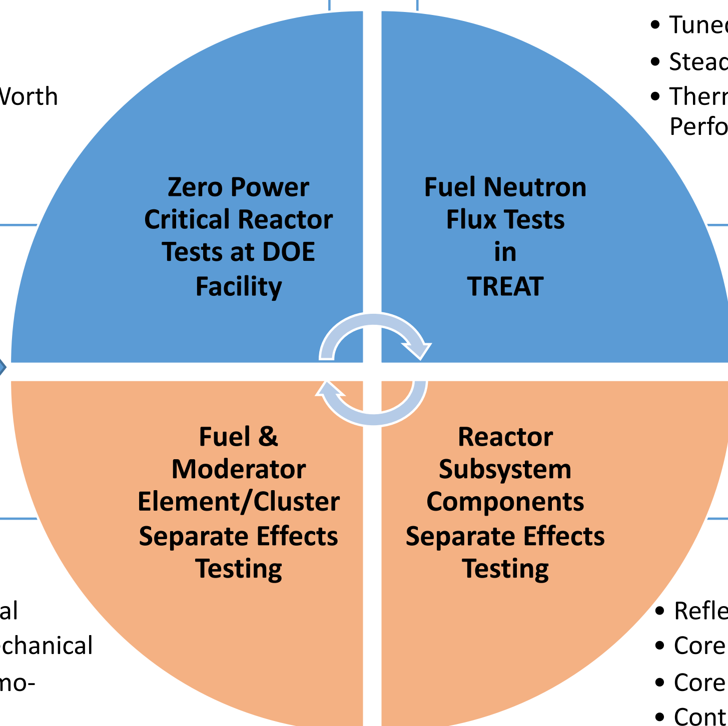
Nuclear Tests Simulating Reactor Physics & Fission Heating Environments

- Criticality Measurements
- Representative Materials
- Representative Spectrums
- Reflector and Control Material Worth

- Fission Generated Heating
- Tuned Power Ramp Rates
- Steady State Power Holds a Low Power
- Thermal-Mechanical Transient Performance

Game Changing Development Conceptual Feasibility

Reactor Component Design & Fabrication Development



Design Analysis Methods and Codes Validation

Prototype Preliminary Design Review (PDR)

- Fuel Element Thermo-Mechanical
- Moderator Element Thermo-Mechanical
- Fuel/Moderator Clustered Thermo-Mechanical Coupling

- Reflector
- Core Support Plate
- Core Periphery
- Control Device Actuators
- Lateral Support, Internal Shield, ...

Non-Nuclear Tests Simulating Thermal/Fluids/Structural Operating Environments

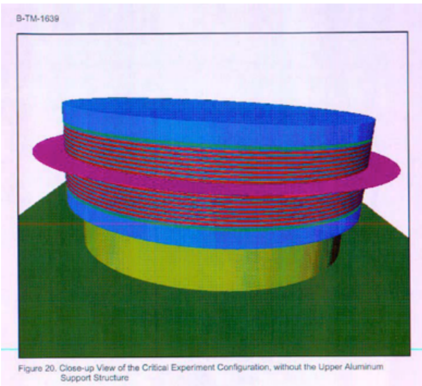
CFEET | NTREES

NTP REACTOR GROUND DEVELOPMENT STRATEGY

Zero Power Critical Assembly Options

NNSS DAF Option

Material Stacking on Planet
JIMO Project Prometheus

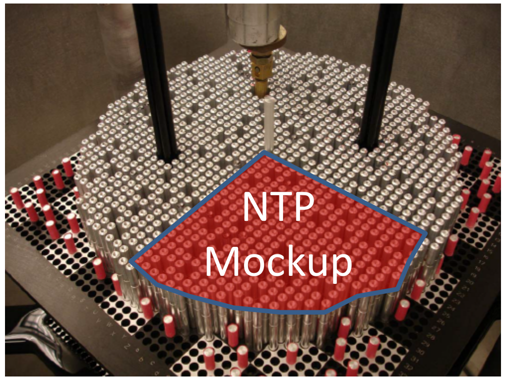


- **Capabilities**
  - Integral Reaction Rates
  - Flux Spectrum
  - Critical Mass
  - Multiple Arrangements
  - Clean Benchmark Cases
  - Mimic HALEU

NOT RECOMMENDED
Encourage DOE to Complete
Fundamental Benchmark Experiments

DOE SNL Option

Fuel Config in H2O Pool
SNTP CX & other Benchmarks



- **Capabilities**
  - Relevant Flux Spectrum
  - Critical Mass Estimates
  - Multiple Arrangements
  - Relevant Power Shapes
  - Clean Benchmark Cases
  - Reactivity Coefficients
  - Assess Kinetics Parameters
  - Use HALEU in NTP Section

RECOMMENDED
Most Cost Effective Approach

DOE INL Option

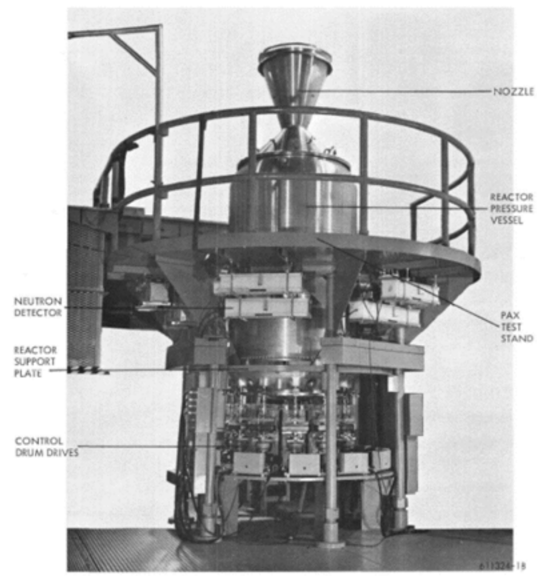
Material Configurations
SP-100, HTRE, SIR

- **Capabilities**
  - Same as SNL Option
  - Mimic External Structures
  - Mimic HALEU

DEACTIVATED

New Full-Scale Full-Detail Facility

Prototypic Fuel & Moderator
WANL, NERVA, FCS/NCX/PAX



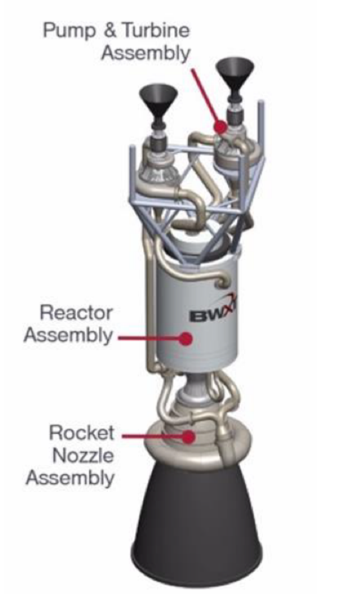
- **Capabilities**
  - Same as Simpler Assemblies
  - Effect of Reflector & Shield
  - Control Swing
  - Minimal Arrangements
  - Highly Developed Fuel/Mod

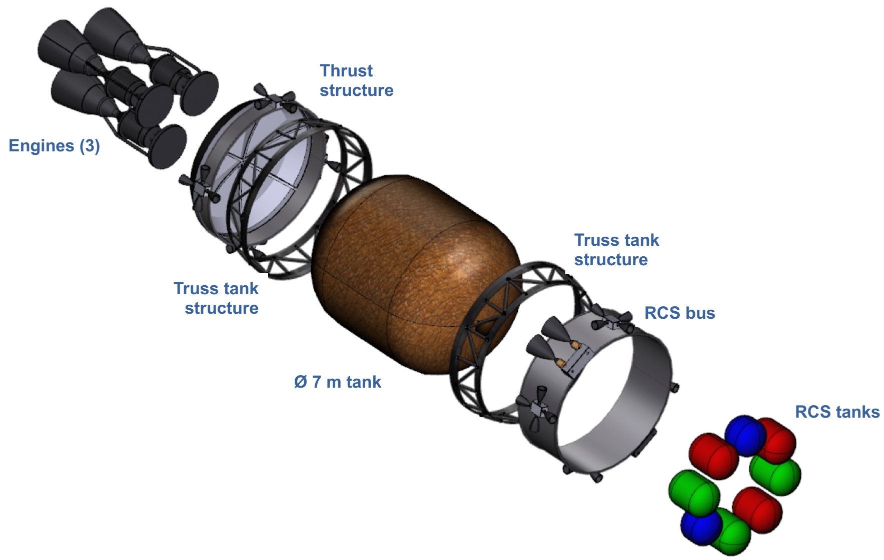
NOT RECOMMENDED – PREMATURE
Can get 90% of required data for
<50% of the cost

NTP TECHNOLOGY DEVELOPMENT CHALLENGES

Integrated Exploration System Considerations

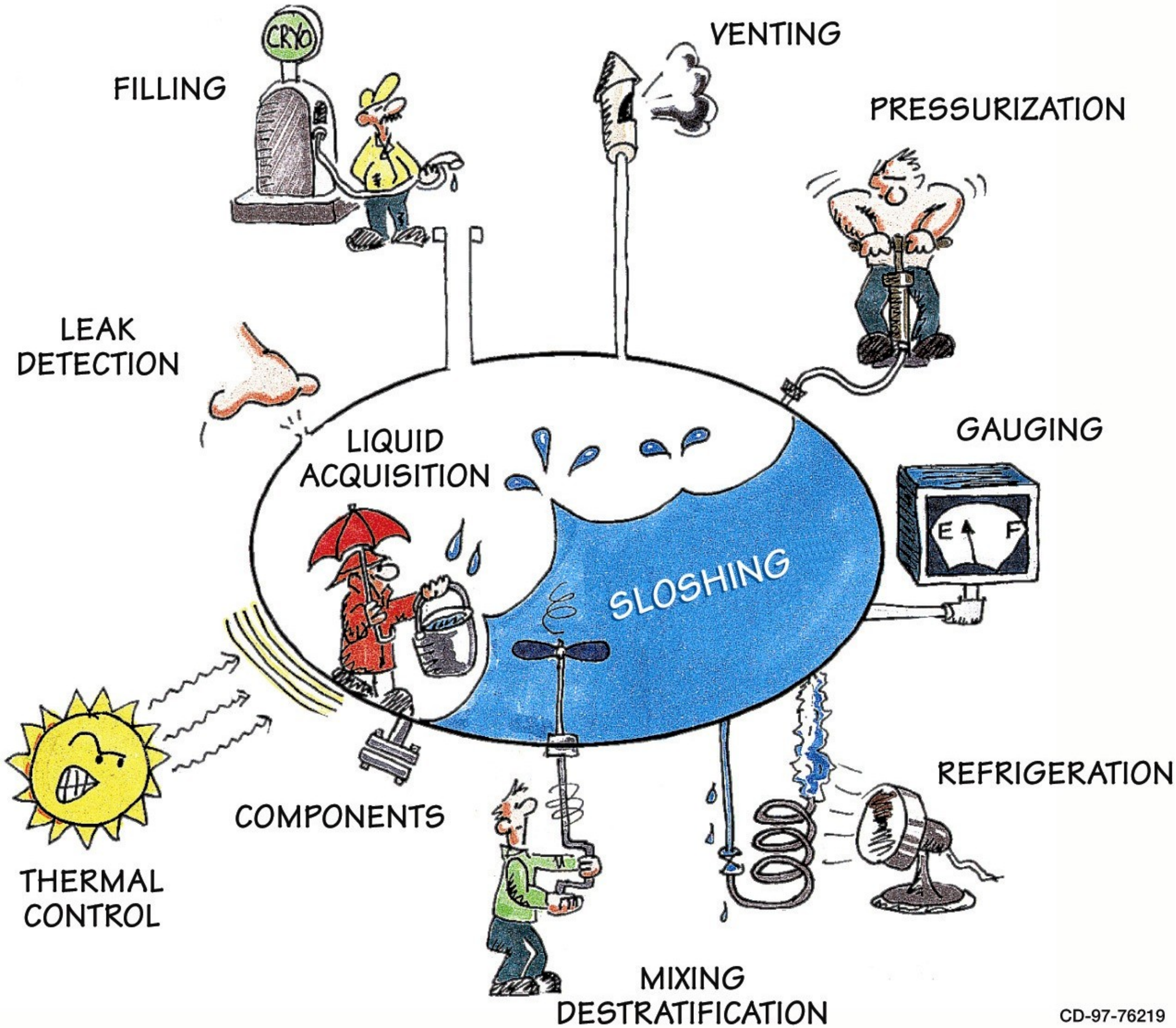
- **Nuclear Fuels/Reactor**
  - High-Temperature/High-Power-Density Fuel
    - Melt Line Margins
    - Durability, Erosion, Fission Product Retention
    - Material Properties – Ductility, CTE, etc.
  - Unique Moderator Element/Control Drums/Pressure Vessel
  - Operational Life / Restarts
  - Space Environments
- **Integrated Engine System**
  - Thermalhydraulics & Flow Distribution
  - Structural Support
  - Turbopump, Nozzle & Other Ex-Reactor Components
- **Integrated Stage**
  - Acceptable Ground Test Strategy
  - Hydrogen CFM
- **Additional Deep Space Exploration Consideration**
  - Power Generation & Storage
  - Aerocapture / Entry Descent & Landing
  - Long-Duration High-Reliability Life Support & Crew Health Mitigation





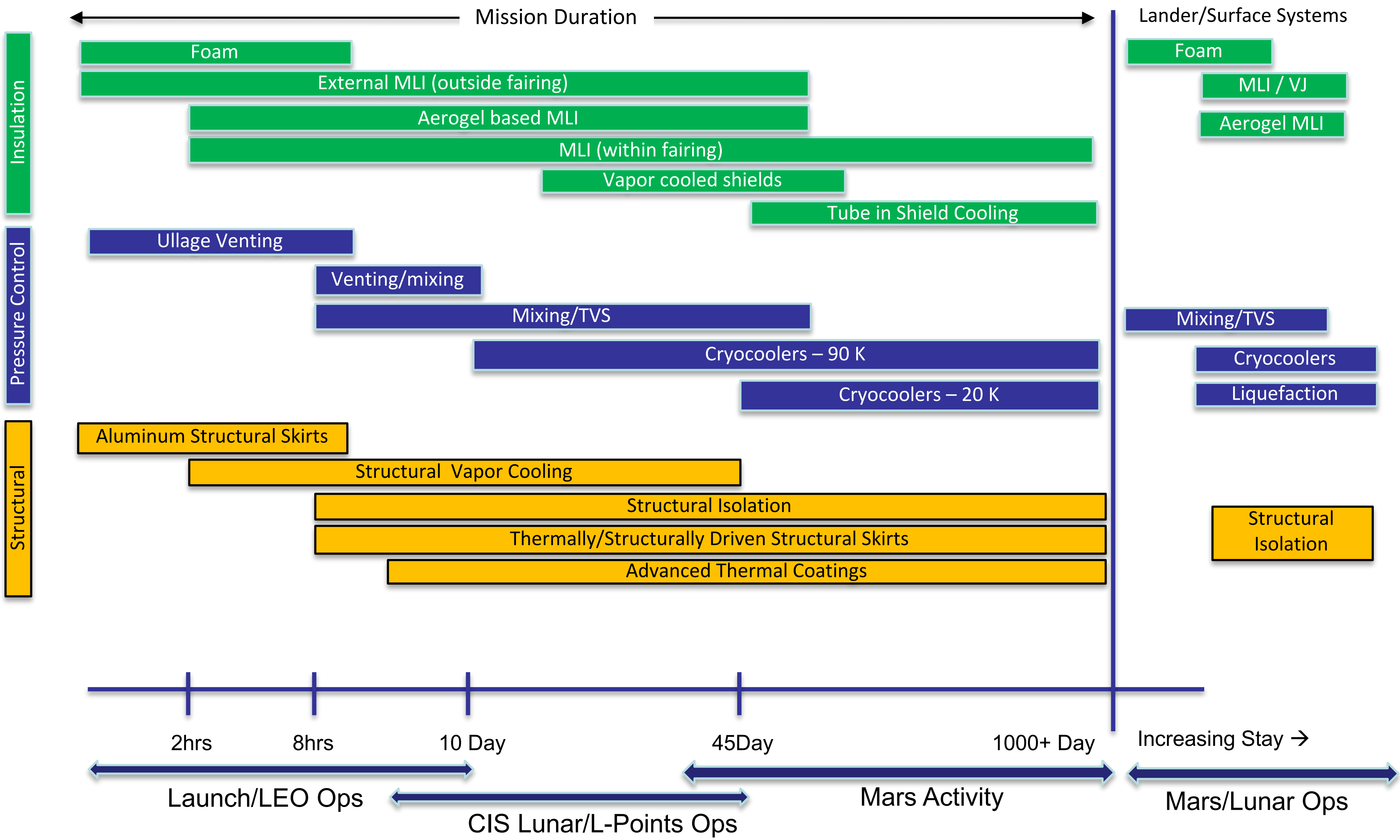
NTP TECHNOLOGY DEVELOPMENT CHALLENGES

CFM Operations



CFM TECHNOLOGY DRIVERS

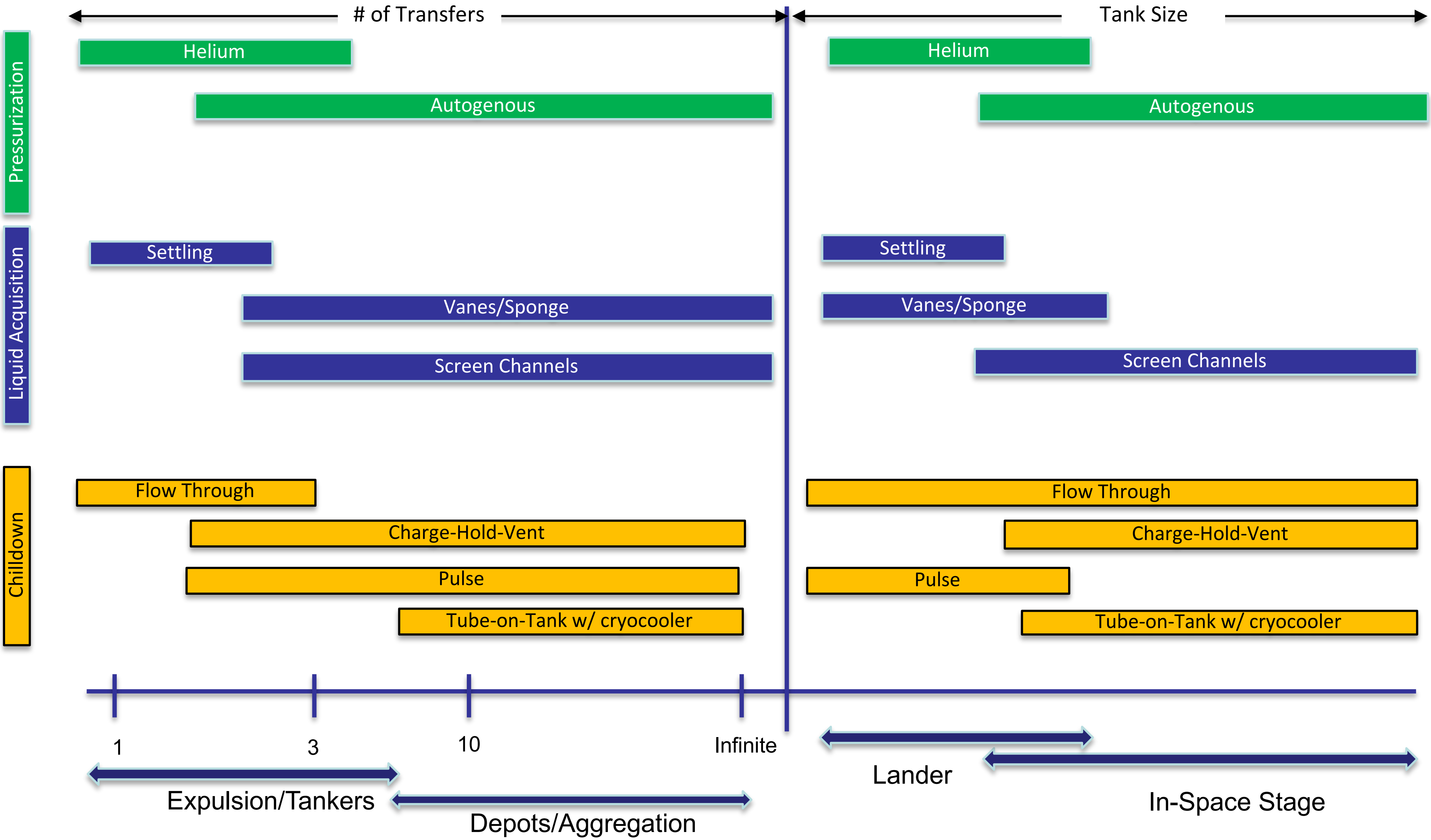
Thermal Management



In-Space CFM SOA: Centaur Upper Stage (3-Layers MLI with ≈14hrs Duration)

CFM TECHNOLOGY DRIVERS

Fluid Transfer



<u>Other CFM Technologies</u>:
Mass Gauging - Independent of mission time and number of transfers – as needed operationally (settled or unsettled)

CFM TECHNOLOGY MATURATION

Development Status & Need

25 CFM technologies identified to support an In-Space Stage and a Lander/Ascent Vehicle
Relative importance of these technologies is dependent on architecture & mission

CFM Elements					
Technologies	Current TRL	TRL at end of eCryo	Gravity Dependant (Y/N)	Path to TRL 6	"Cross Cutting" or "Fluid Specific"
Low Conductivity Structures	5	5	No	Ground Test	Cross Cutting
High Vacuum Multilayer Insulation	5	6	No	Ground Test	Cross Cutting
Tube-On-Shield BAC	5	5	No	Ground Test	Cross Cutting
Valves, Actuators & Components	5	5	No	Ground Test	Cross Cutting
Helium Pressurization	5	5	Yes	Flight Demo	Cross Cutting
MPS Line Chilldown	5	5	Yes	Flight Demo	Cross Cutting
Pump Based Mixing	5	5	Yes	Flight Demo	Cross Cutting
Termodynamic Vent System	5	5	Yes	Flight Demo	Cross Cutting
Tube-On-Tank BAC	5	5	Yes	Flight Demo	Cross Cutting
Unsettled Liquid Mass Gauging	5	6	Yes	Flight Demo	Cross Cutting
Liquid Acquisition Devices	5	5	Yes	Flight Demo	Fluid Specific
Advanced External Insulation	3	3	No	Ground Test	Can Be Both
Automated Cryo-Couplers	3	3	No	Ground Test	Cross Cutting
Cryogenic Thermal Coating	3	3	No	Ground Test	Cross Cutting
High Capacity, High Efficiency Cryocoolers 90K	3	3	No	Ground Test	Cross Cutting
Soft Vacuum Insulation	3	3	No	Ground Test	Cross Cutting
Structural Heat Load Reduction	3	3	No	Ground Test	Cross Cutting
Propellant Tank Chilldown	3	3	Yes	Flight Demo	Cross Cutting
Transfer Operations	4	4	Yes	Flight Demo	Cross Cutting
High Capacity, High Efficiency Cryocoolers 20K	3	3	No	Ground Test	Fluid Specific
Liquefaction Operations (MAV & ISRU)	3	3	No	Ground Test	Fluid Specific
Para to Ortho Cooling	4	4	No	Ground Test	Fluid Specific
Vapor Cooling	4	6	No	Ground Test	Fluid Specific
Propellant Densification	4	4	No	Ground Test	Fluid Specific
Autogenous Pressurization	4	4	Yes	Flight Demo	Fluid Specific

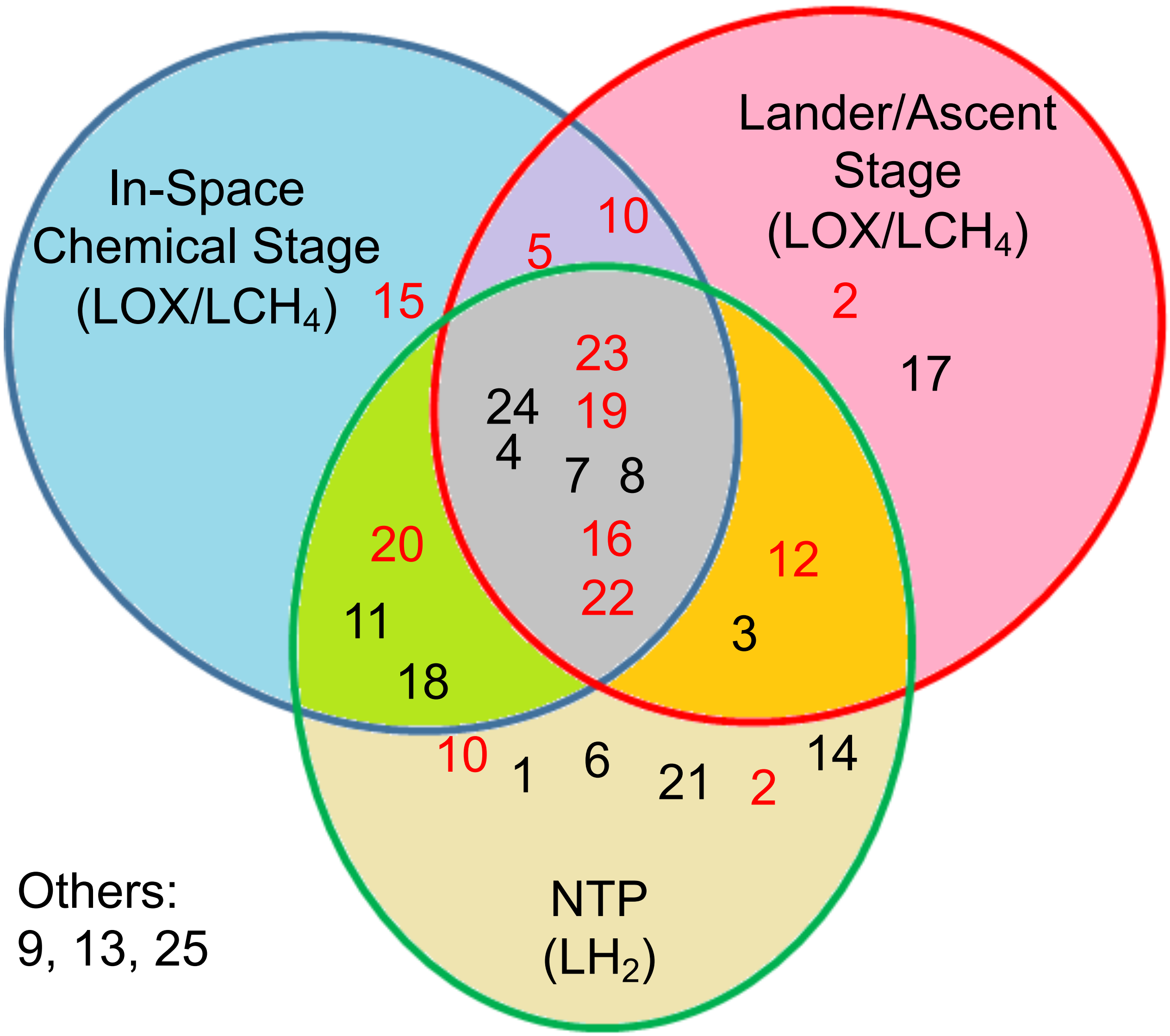
Can achieve TRL 6 through ground testing.

Flight Demo required to achieve TRL 6.

Technology "Long Poles" Development is needed.

CFM TECHNOLOGY MATURATION

Architectural Venn Diagram



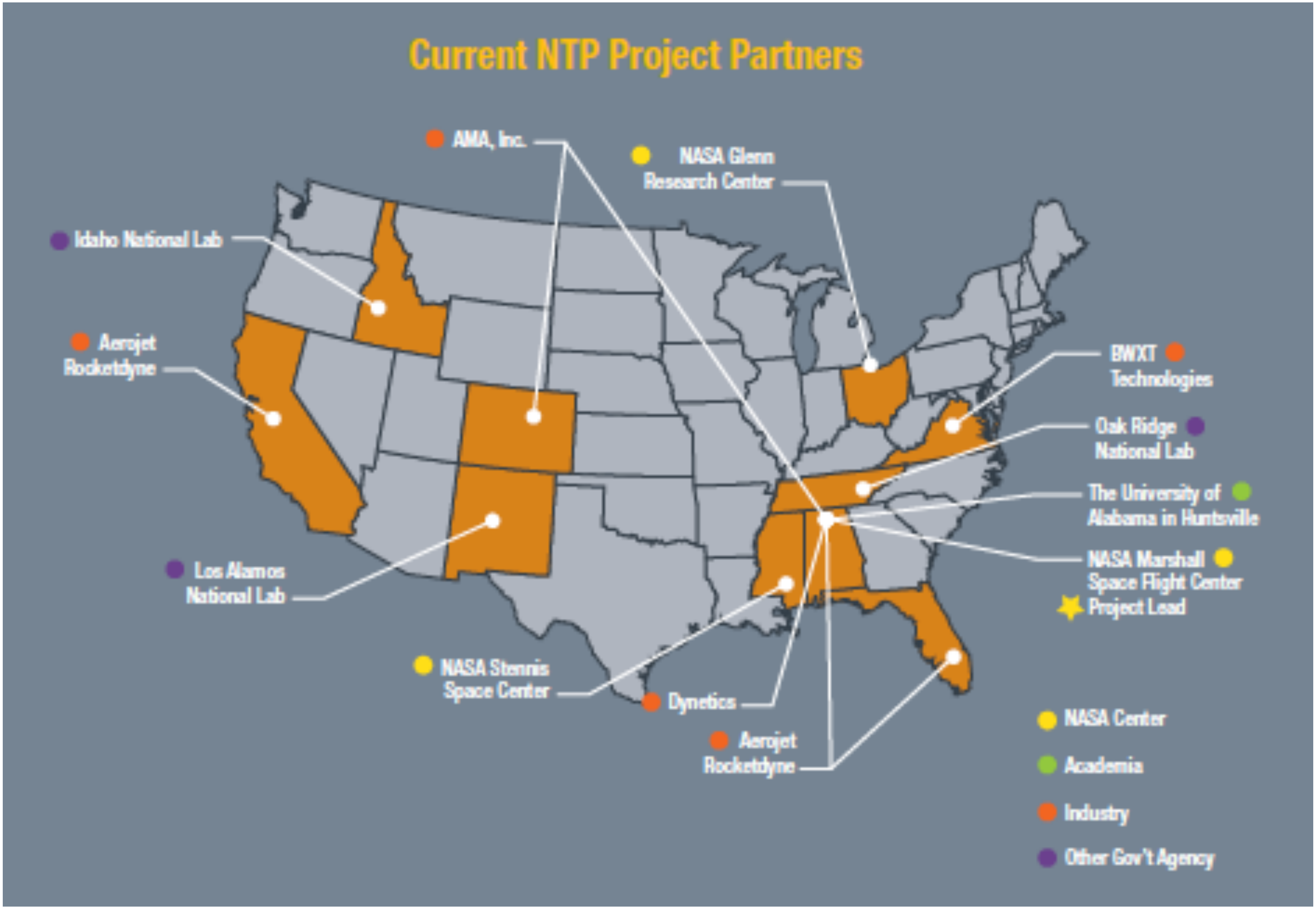
Others:
9, 13, 25

Technology	No
Advanced External Insulation	1
Autogenous Pressurization	2
Automated Cryo-Couplers	3
Cryogenic Thermal Coating	4
Helium Pressurization	5
High Capacity, High Efficiency Cryocoolers 20K	6
High Capacity, High Efficiency Cryocoolers 90K	7
High Vacuum Multilayer Insulation	8
Liquefaction Operations (MAV & ISRU)	9
Liquid Acquisition Devices	10
Low Conductivity Structures	11
MPS Line Chilldown	12
Para to Ortho Cooling	13
Propellant Densification	14
Propellant Tank Chilldown	15
Pump Based Mixing	16
Soft Vacuum Insulation	17
Structural Heat Load Reduction	18
Termodynamic Vent System	19
Transfer Operations	20
Tube-On-Shield BAC	21
Tube-On-Tank BAC	22
Unsettled Liquid Mass Gauging	23
Valves, Actuators & Components	24
Vapor Cooling	25

- **Red numbers indicate technologies that need to fly to reach TRL-6**
- **Fluid specific technologies may be captured in multiple locations**
- **Does not capture effects of scale**

NTP PROJECT TEAMING STRATEGY

A Diversified Public-Private Partnership



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