Affordable Development and Implementation of Nuclear Thermal Rockets for Mars Missions

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Outline

- Motivation and Background
- Design Tools
- “Evolutionary” Mars Sample Return
- “Revolutionary” Mars Sample Return
- Summary
- Future Work

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Motivation

- NTRs recognized as only solution to human exploration of near planets in near to mid-term time frame
  - Large payloads
  - Faster transit times
- Reservations over projected costs, current need, and technology misconceptions

Goals

1. Show that NTRs enable human missions
2. Show that NTRs are applicable and financially feasible for near-term non-human missions (Mars sample return)
3. Provide cost-effective method and schedule for development and implementation

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NTR History

- NERVA successfully demonstrated technology with graphite fuel
  - Over 17 hours run time
  - 28 restarts of a single engine
  - $1.4B program in 1972 – $7.6B today
- Modern concepts using W-Re cermet fuels
  - Improved fuel integrity
  - Projected I_{sp} (s) = 900-950
  - Example – Pratt & Whitney's Triton

	Pewee 1*	Triton
Mass (kg)	2,570	2054
Thrust (lbf)	27,000	25,000
I_{sp} (s)	845	911
Reactor Power (MW)	503	525

* With graphite fuel.

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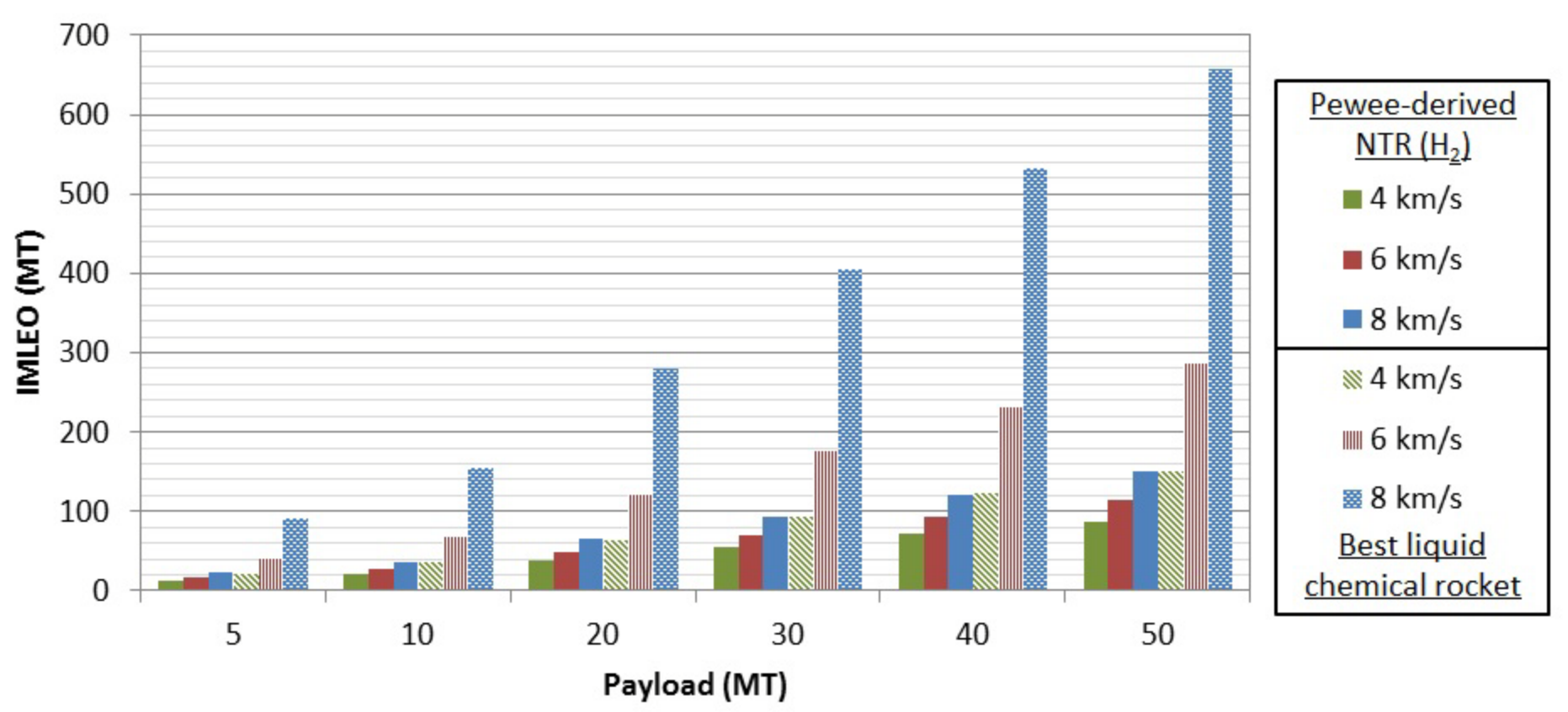
Affordable NTR Concept

1. Build Pewee-derived engine with W-Re cermet fuel
   - Minimal changes to original design → low development cost
   - Less than 2 hours total run time → cheaper fuel qualification process than long-term terrestrial fuel
   - Prove in space with unmanned mission
2. Build new reactor that is highly optimized for W-Re cermet
   - Apply to human missions and large unmanned missions

NTR Versus Chemical Propulsion – Performance for Typical Mission ΔV's



- Masses of NTR options increase if LOX augmentation is employed (still outperforms chemical)
- Masses increase exponentially with increasing ΔV

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Interplanetary Trajectory Optimization

- Assumptions
  - Impulsive burns
  - Planet positions from propagated static ephemerides
- Capabilities
  - Global optimizer
  - Elliptic planet trajectories
  - 3-D spacecraft trajectories
  - Plane changes
  - Parking orbits
  - ΔV's from aerocapture/aerobraking
  - Limit entry interface velocities
  - Specify stay times/times of flight
  - Type 1 and Type 2 trajectories (only Type 1 used for this project)

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Interplanetary Trajectory Optimization

- Value to minimize – IMLEO (kg)
- Design variables
  - Launch date
  - Time-of-flight to Mars
  - Stay time at Mars
  - Time-of-flight to Earth
- Additional output
  - ΔV budget
  - Mass budget
  - Positions and velocities

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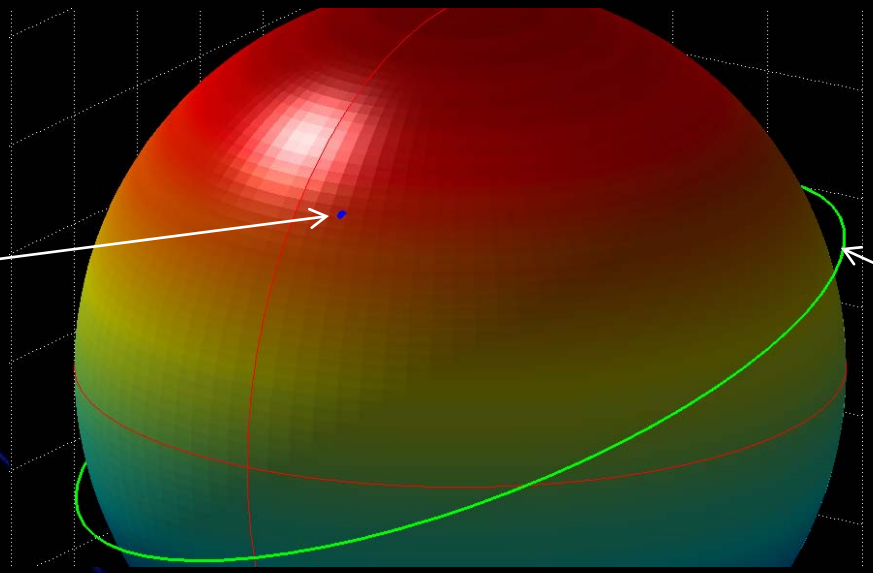
Launch Trajectory Optimization

- Solve boundary-value problem for launch trajectory
- Minimize propellant mass

Initial Conditions (Launch Site)
- Latitude
- Longitude
- Elevation
- Launch site inertial velocity



Final Conditions (Orbit)
- Semi-major axis
- Eccentricity
- Inclination
- Longitude of ascending Node
- Argument of periapsis

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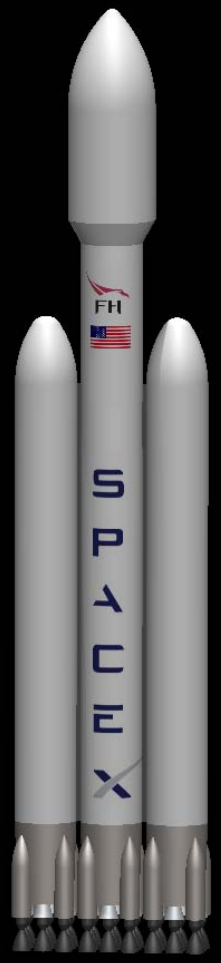
2010 Planetary Science Decadal Survey

- Planned NASA Mars sample return mission
  - Next in Flagship class
  - 2018-2024 timeframe
  - Approximately $6 billion
- Three launches of Atlas V 531-551
  - Science package – combined science/collection rover
  - Orbiter – telecom, TEI, Earth entry vehicle
  - Lander – Mars ascent vehicle, fetch rover

Evolutionary – Architecture

- Science package, lander, and orbiter are identical to PSDS
- Single SpaceX Falcon Heavy replaces three Atlas V launches
  - Trans-Mars injection – single Pewee-derived NTR instead of three Atlas V third stages (volume and mass savings)
  - Money saved on launch costs pays for NTR development and testing



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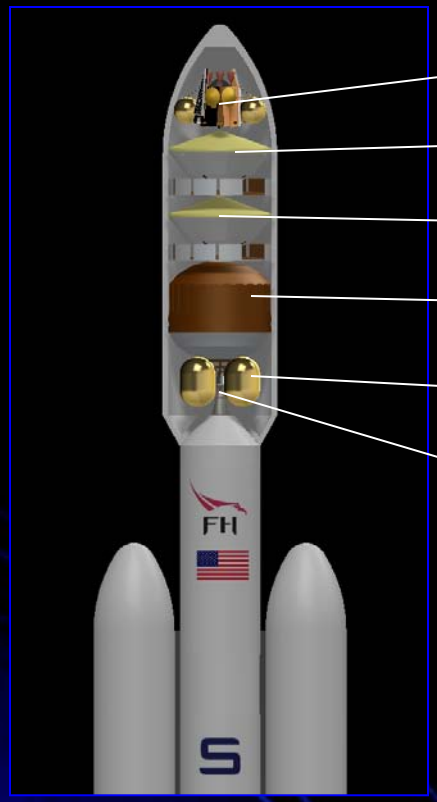
Evolutionary – Mass Budget



Orbiter

Lander / MAV

Rover

TMI H_2 Tank

TMI LOX Tanks

NTR Engine & Shield

Structure etc.

Components for LOX Augmented Design	Mass (kg)
Orbiter	3,270
Lander / MAV	4,668
Rover	4,457.4
TMI H_2 Propellant + Tank	4461
TMI LOX Propellant + Tanks	17,841
NTR Engine w/ Radiation Shield	3,055
Structure etc.	2,136.6
TOTAL MASS TO LEO	**39,889**

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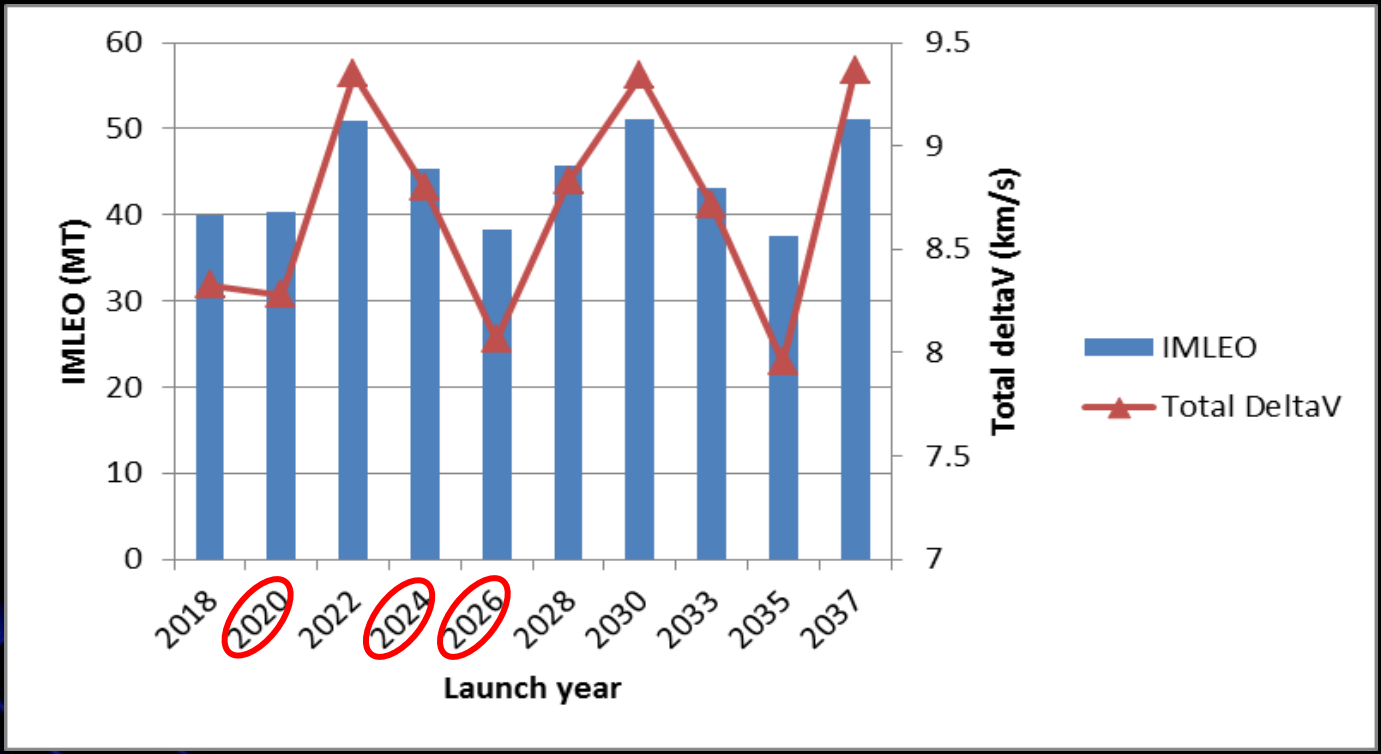
Evolutionary – Launch Opportunities



Preferred	Required
IMLEO < 45 MT	IMLEO < 51 MT
Launch before 2026	

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Evolutionary – Cost Analysis

	Decadal Survey MSR	NTR Augmented MSR
MAX-C Rover	1,823.40	1,823.40
Orbiter	805.17	805.17
Lander	1876.74	1876.74
MSRH	475.74	475.74
NTR	0	712.16
Launch Costs	776.6	149.55
Phase E Costs	341.5	338.02
Total	**6,099.15**	**6,180.78**

*$M in 2015 Dollars

Project Management/SE/MA	92.70
Fuel Development & Certification	85.53
Engine Development	238.01
Engine Testing	59.59
Launch Facility Upgrades	11.18
Launch Ship Upgrades	31.12
Security Upgrades	11.72
Fuel Costs	21.24
Education / Outreach Upgrades	23.15
NTR Reserves	137.91

Notable differences from PSDS

- Single launch changes timeline – lander waits in orbit while large rover collects samples
- Rover budget was altered after the PSDS was issued – this does not change relative cost of missions

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Evolutionary – Cost Analysis

- $7.6 Billion in 2011 dollars already invested in NTR development
- ~5yr NTR Development includes:
  - Construction of 2 cermet Pewee-derived NTRs
    - Test engine
    - Flight engine
  - SAFE testing in Nevada
  - Fuel development and certification
  - 30% reserves
- ~$100M more than PSDS w/ NTR costs

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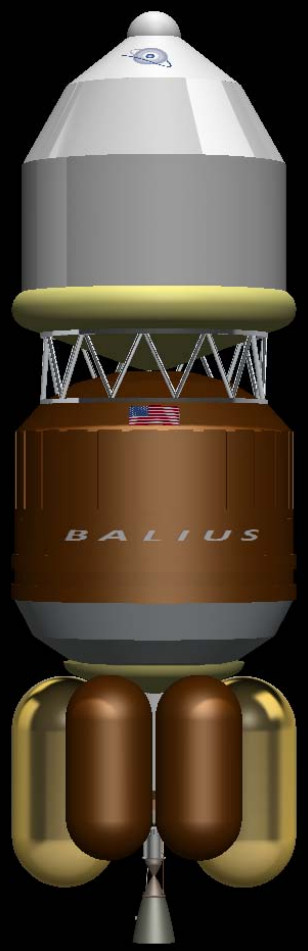
Revolutionary NTR MSR Mission

- Triton-derived NTRs
  - Interplanetary transfers
  - Mars descent, landing, and ascent
- Can return ~100 kg of samples instead of ~1 kg from chemical missions
- Mars Hopper enables collection of samples from all over Mars' surface



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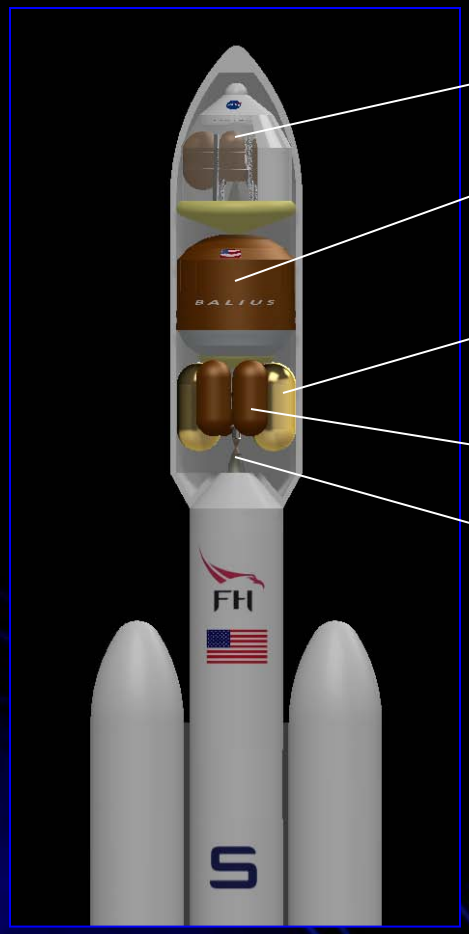
Revolutionary – Mass Budget



	Component	Mass (kg)
Service Module	NTR & Radiation Shield	1682
	Structure, Thermal, Communication, etc..	978
	Power (Solar)	250
	LH_2 Recondenser	56
	Sample Reentry Components	350
	TMI/MOC Propellant & Tank	21485
	TEI Propellant	1198
Mars Ascent Vehicle	NTR & Radiation Shield	1682
	Structure, Thermal, Communication, etc..	683
	Power (Bimodal NTR)	175
	Secondary Power (Battery)	8
	Rover	70
	Propellant Collection & Recondenser	297
	Inflatable Descent Components	543
	Propellant & Tank	1012
	TOTAL MASS TO LEO	**30470**

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Revolutionary – Architecture

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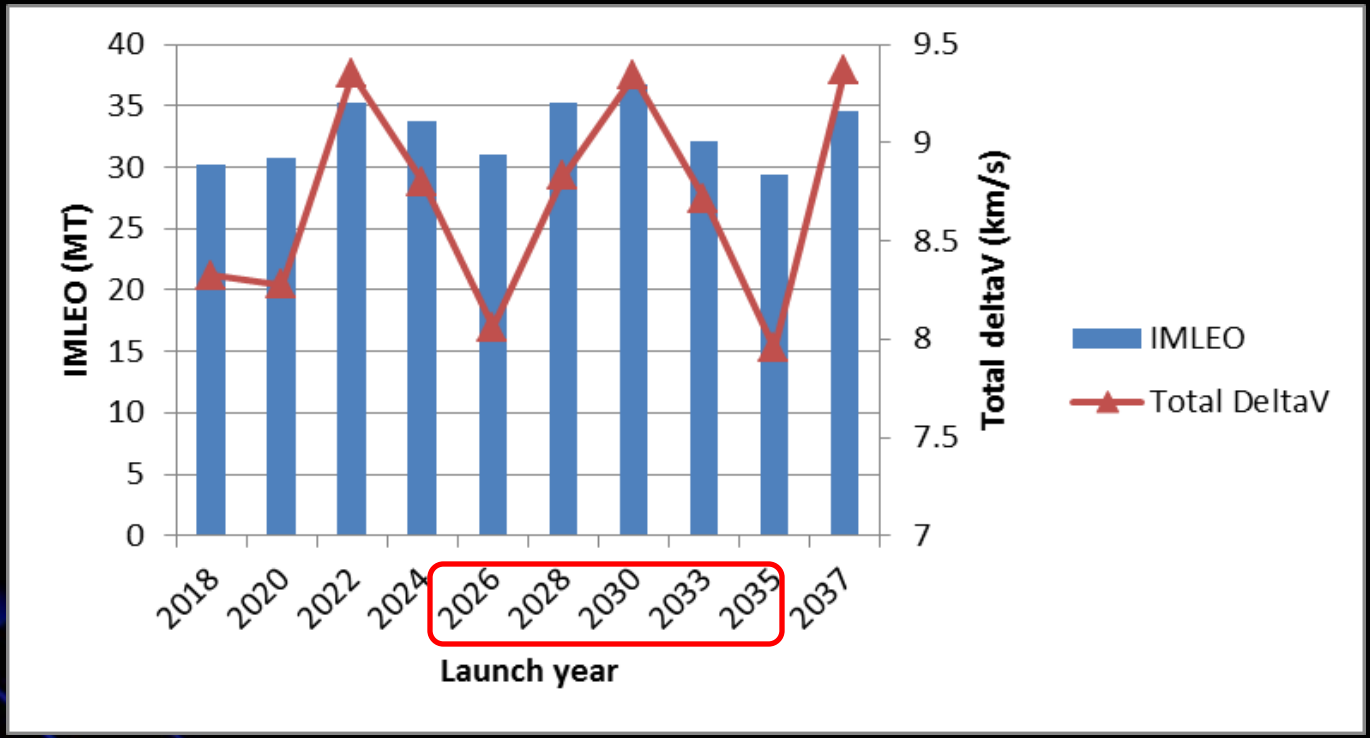
Revolutionary – Launch Opportunities



Preferred	Required
IMLEO < 35 MT	IMLEO < 51 MT
Launch before 2035	

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Revolutionary – Cost Analysis

	Evolutionary	Revolutionary
Rover / Hoppers	1,823.40	1,871.67
Orbiter	805.17	1003.82
Lander	1876.74	2849.77
MSRH	475.74	99.67
NTR	712.16	990.9
Launch Costs	149.55	311.85
Phase E Costs	338.02	590.34
Total	**6,180.78**	**7,718.02**

*$M in 2015 dollars.

- Cost estimates much more difficult
  - Technology less developed
  - Larger extrapolations
  - Less comparable baseline metrics

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Summary – Missions

	PSDS	Evolutionary	Revolutionary	Manned
Trans-Mars Injection	Chemical	Pewee-derived NTR	Triton-derived NTR	Triton-derived NTR
Mars Orbit Insertion	Chemical	Chemical	Triton-derived NTR	Triton-derived NTR
Trans-Earth Injection	Chemical	Chemical	Triton-derived NTR	Triton-derived NTR
Earth Orbit Capture	Chemical	Chemical	Triton-derived NTR	Triton-derived NTR
Entry, Descent, and Landing Method	Parachute / Sky Crane	Parachute / Sky Crane	HIAD / retropropulsion	HIAD / retropropulsion
IMLEO (kg)	48,513	39,889	30,465	632,000
Current TRL	5	5	4	2-3

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Summary – Mission Goals

- Evolutionary
  - Cost-effective flight test of NTR
- Revolutionary
  - Returns large amount of samples from entire planet
  - Proves bimodal fission surface power
  - Proves in-situ propellant collection
  - Proves high-mass EDL
- Manned mission
  - Accomplishes long-term goal in human exploration
  - Proves technology for further exploration

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Summary – Project Goals

- Evolutionary mission
  - Detailed mission architecture
  - Interplanetary trajectory optimization
  - Mass budget
  - Cost analysis
  - CAD models to illustrate mission
- Revolutionary mission
  - Detailed mission architecture
  - Trajectory optimizations
    - Ascent / Descent
    - Interplanetary
  - Mass budget
  - Cost analysis
  - CAD models to illustrate mission
- Human mission
  - Architecture
  - Trade studies

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Future Work

- Affordable NTR
  - Detailed design and analysis of Pewee-derived NTR with W-Re fuel
  - W-Re fuel development
- Retro Propulsion EDL
  - High-fidelity CFD models
  - Descent trajectory optimization
  - Large mass landing technique

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Questions?

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