

Transformational Propulsion for In-Space Fast Transits

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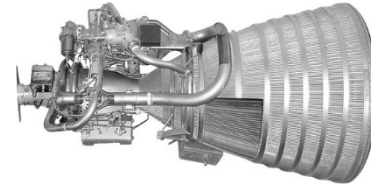
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Outline

- **Motivation**
- **Terms of Reference / Scope / Objectives**
- **Mission Design**
- **Driving Technologies: SOA and Potential**
 - **Nuclear Thermal Propulsion**
 - **Nuclear Electric Propulsion**
 - **Solar Electric Propulsion**
 - **Nuclear Pulsed / Transformational Propulsion**
- **Summary**
- **Recommendations**

Motivation

- The RL10 Represents the SOA in high performance exploration class propulsion
 - 1 x RL10 engine (Artemis 1-3)
 - Exploration Upper Stage, 4 x RL10 engines
 - First tested in 1959 and flown in 1963
- Technologies today are largely the same
 - Largely deflagration of a combustion product passed through a choked nozzle and expanded
 - Even electric propulsion is largely unchanged since the Hall thrusters (1972) and Gridded ion (1964)
 - Yes, Advanced in materials, tweaks to propellant chemistry, new manufacturing...
- Ambitious programs made progress, but no significant resources provided for exploration class transformational space transportation since the 1970s.
 - Project Orion (58-63), NERVA (61-73), etc.
 - Recently constrained to preliminary investigations, low-level technology, studies (NASA, DOE, NIAC, ARPA-E, NSF, etc.), but no recent strategic system development



Transformational propulsion is required for ambitious missions (fast crewed transits, interstellar probe, gravity lens, etc.), but has not received significant investment in 50 years.

Scope / Objectives

Expectation of a quick / high level assessment (~0.5 FTE, 3 months)

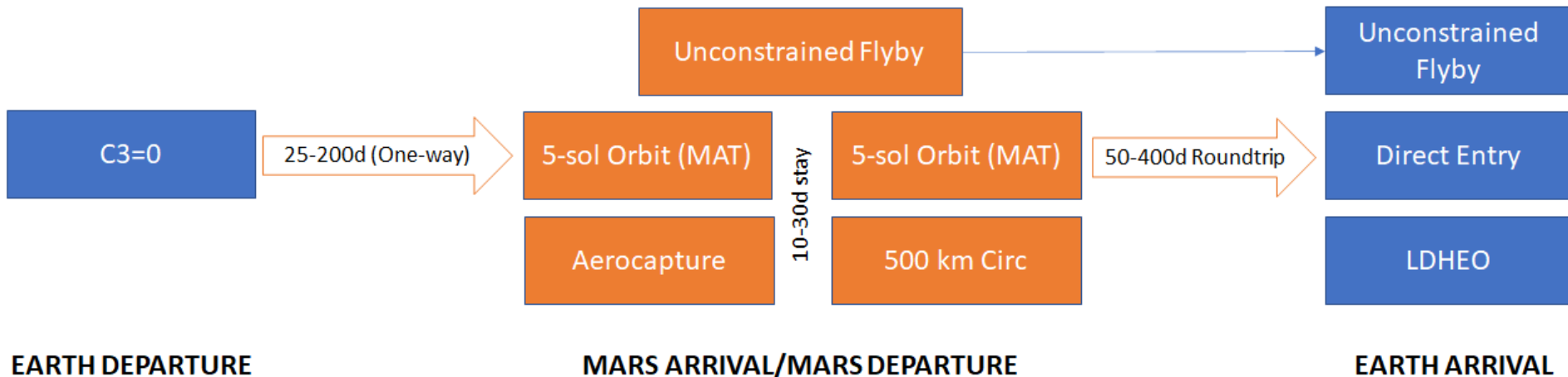
- Literature review
- All Chemical Comparison Assessment
- Conventional Nuclear Thermal propulsion
 - Near-term and lower TRL concepts
- Electric Propulsion
 - Solar electric power generation: near-term and far-term
 - Nuclear electric power generation: near-term and far-term
 - Heat rejection technologies
 - Range of thruster options: Hall Thrusters, VaSIMR, MPDs, etc.
- Unconventional Nuclear (e.g. NIAC concepts)
- Recommendations for near-term investments

What could we achieve with plausible yet transformational propulsion, and what should we do today to make meaningful progress?

Trades / Generalized

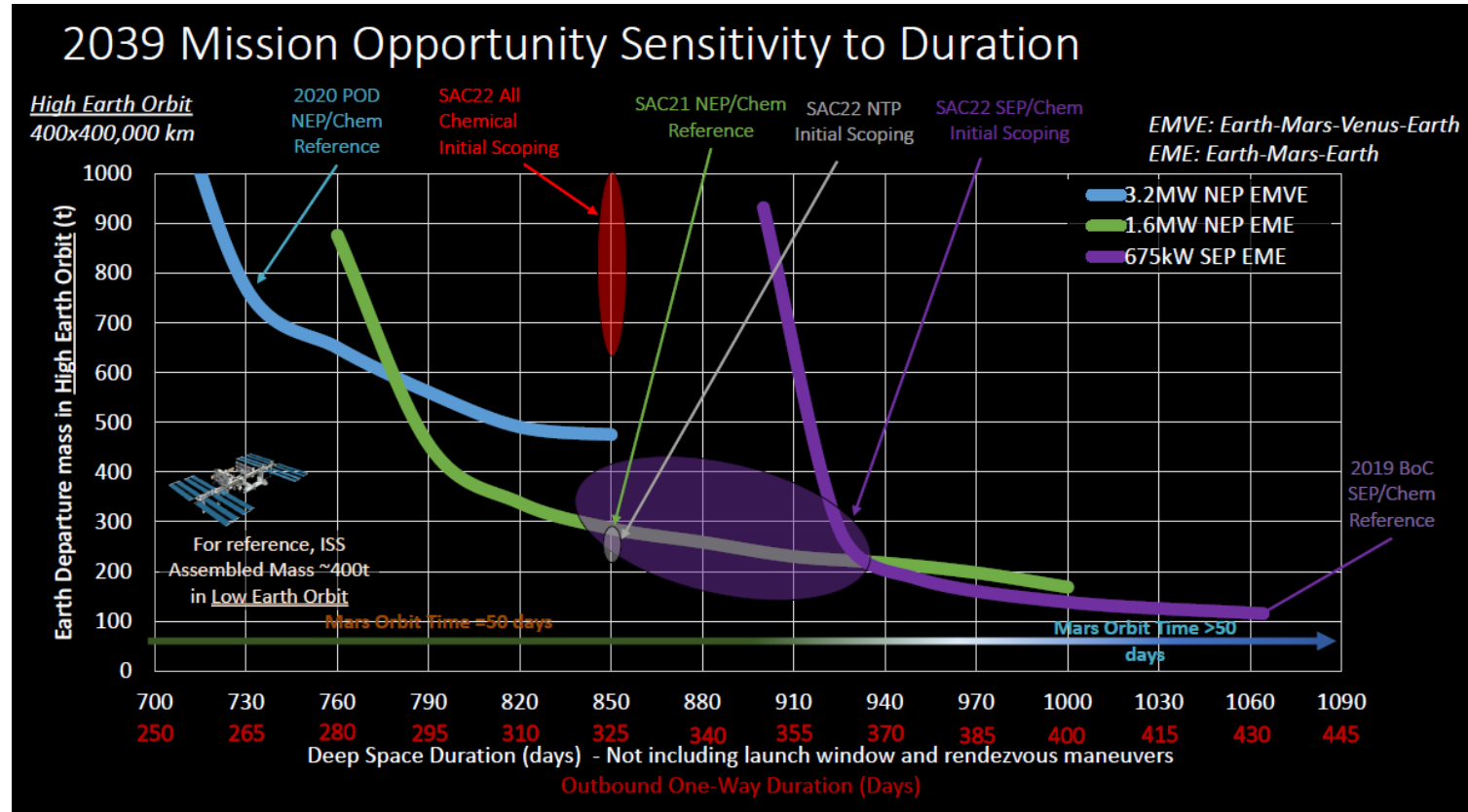
High thrust and Low thrust propulsion systems

- High thrust departure and capture burns with I_{SP} values representative of LOX/LCH₄, LOX/LH₂, and NTR (900-1800s)
- Low thrust burns during interplanetary transits capturing EP propulsion system I_{SP} values from 2,000s to 20,000s

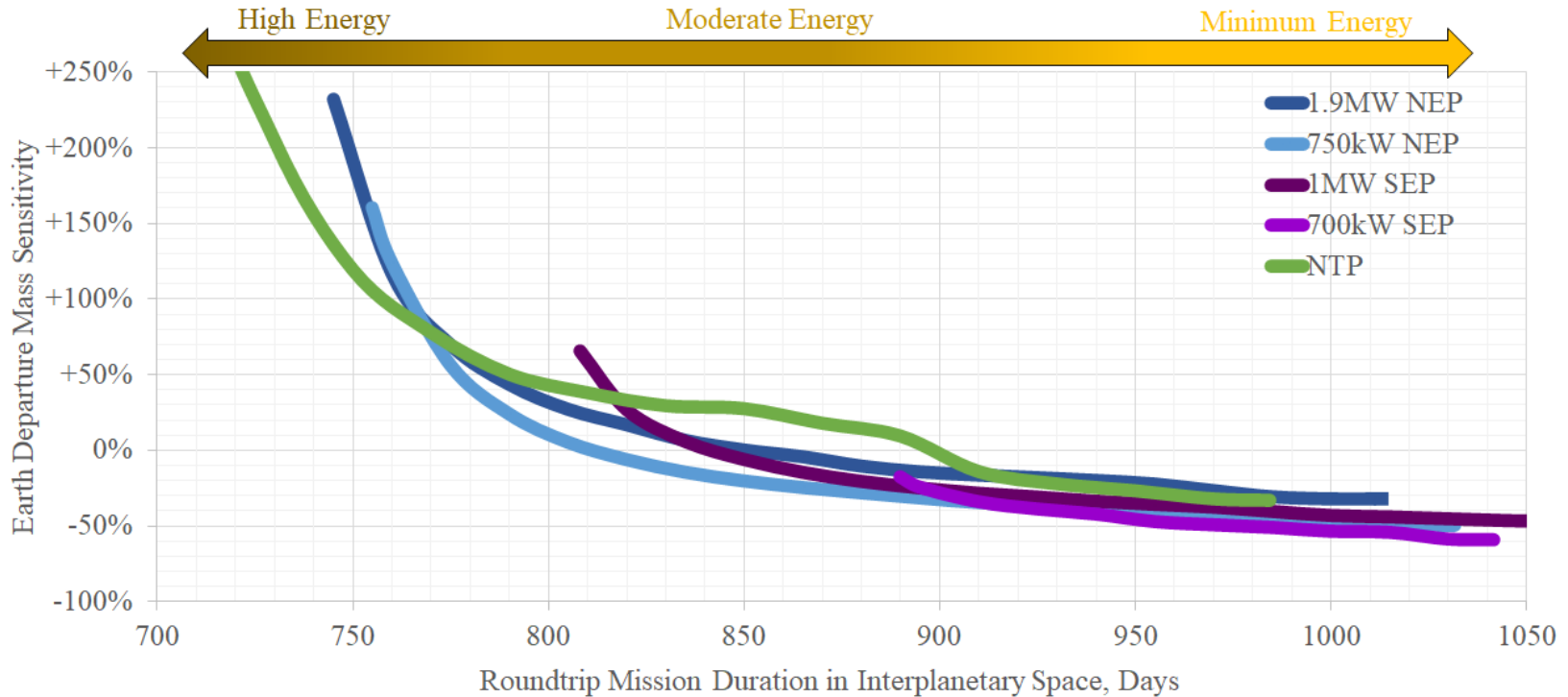


All Results in the Appendix

Subset of Mars Architecture Trades

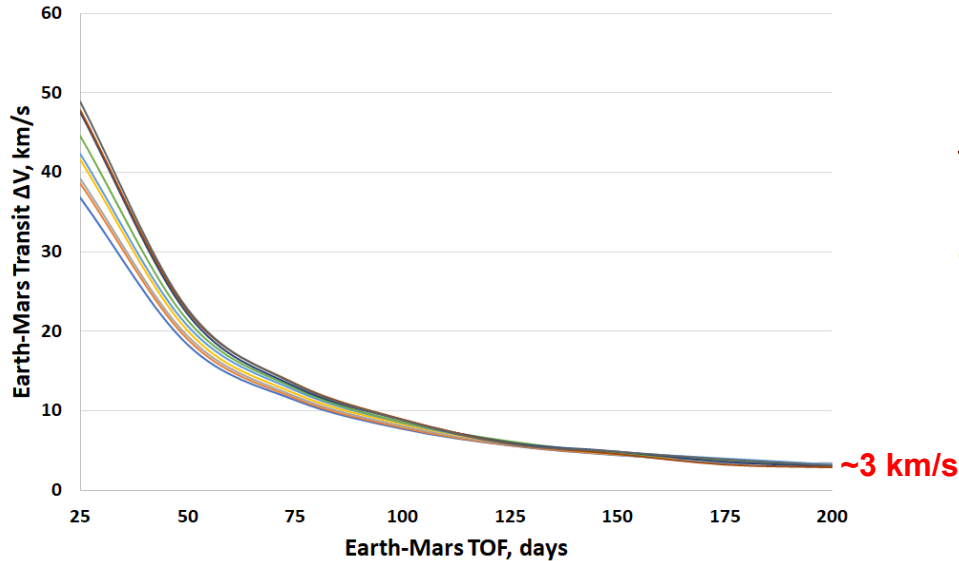


Energy Sensitivities for Conventional Options

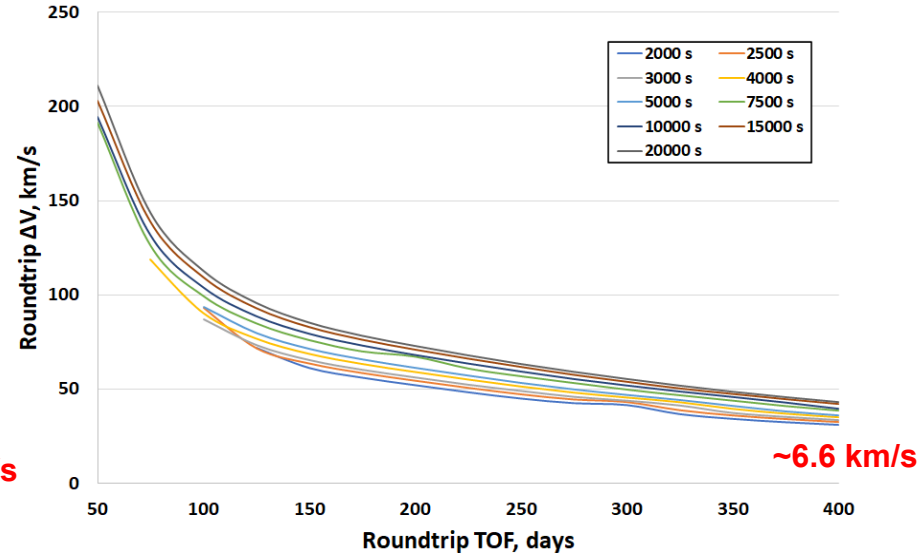


It simply gets really hard really fast...

ΔV for Earth-Mars Transit

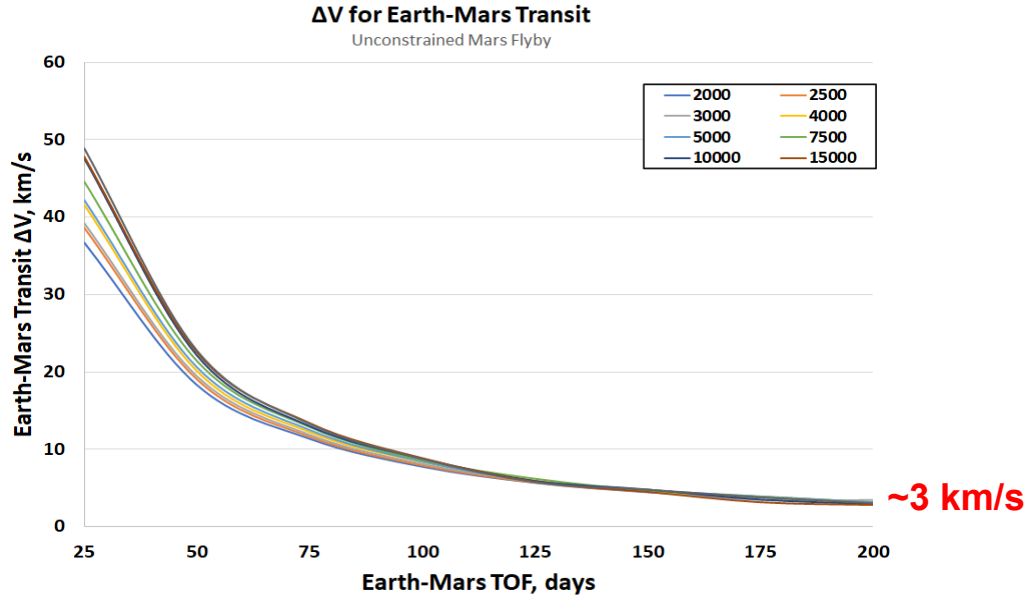


ΔV for Earth-Mars Roundtrip



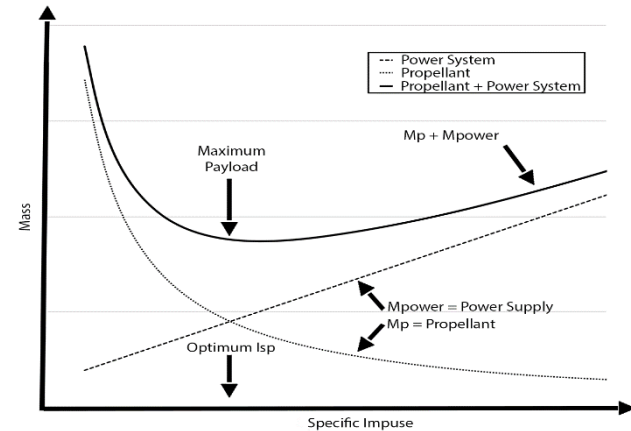
Energy requirements increase by more than an order of magnitude for “rapid” transits.

Performance Drivers



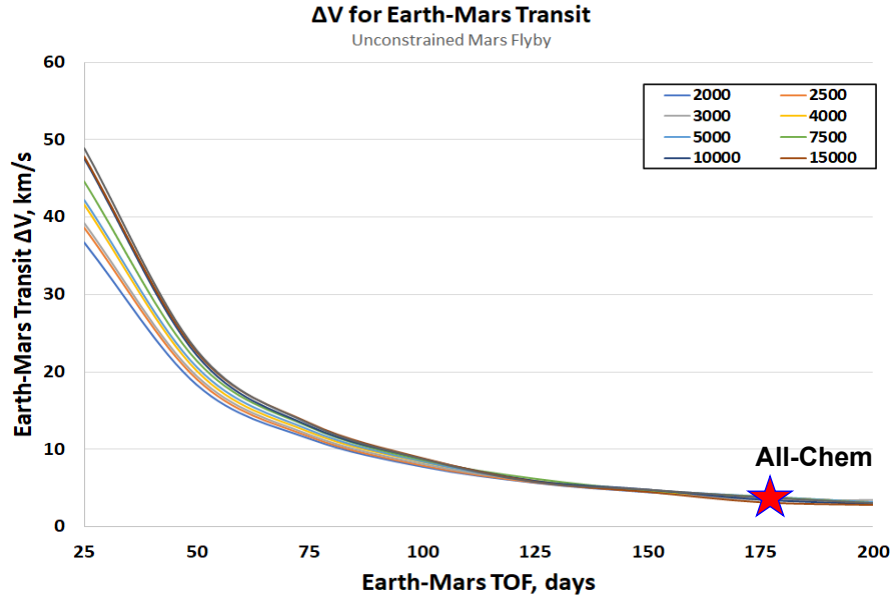
$$MR = \frac{m_f}{m_0} = e^{\frac{\Delta v}{g I_{SP}}}$$

$$P = \frac{g(FI_{SP})}{2\eta}$$



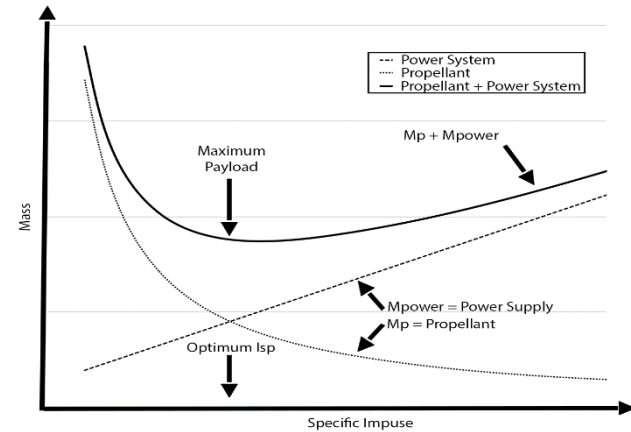
Cannot tolerate a ΔV increase faster than Specific Impulse.
 α_{System} (Kg/kWe) drives the limiting performance.

Performance Drivers



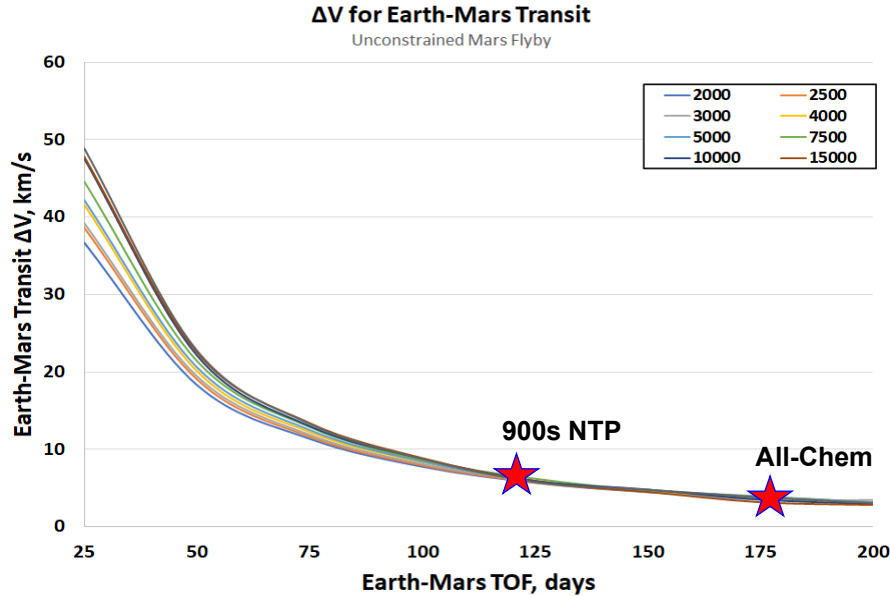
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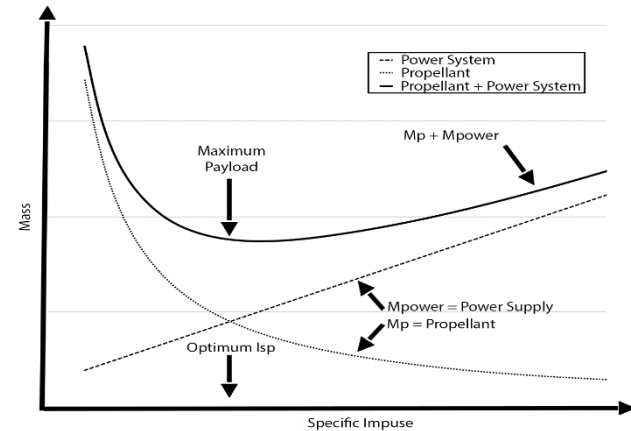
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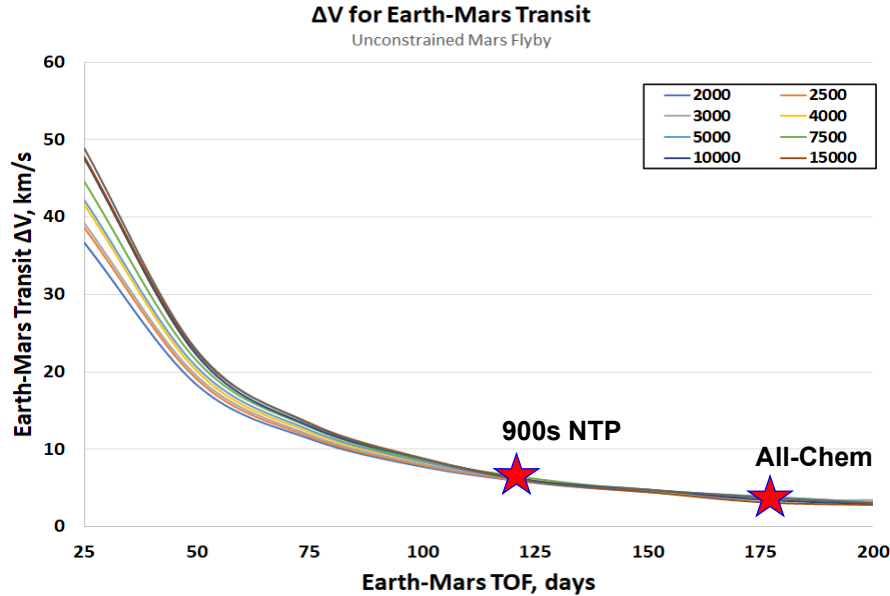
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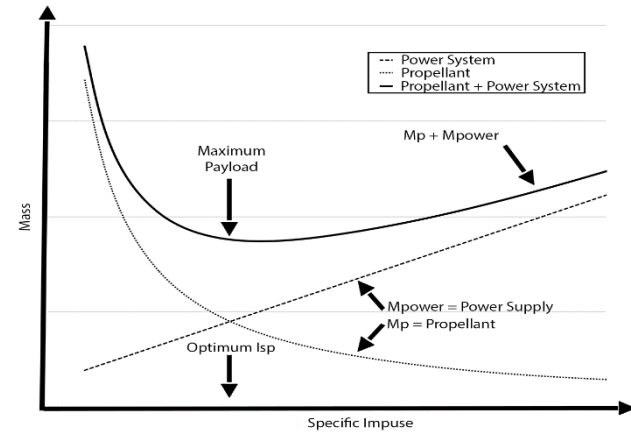
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Performance Drivers



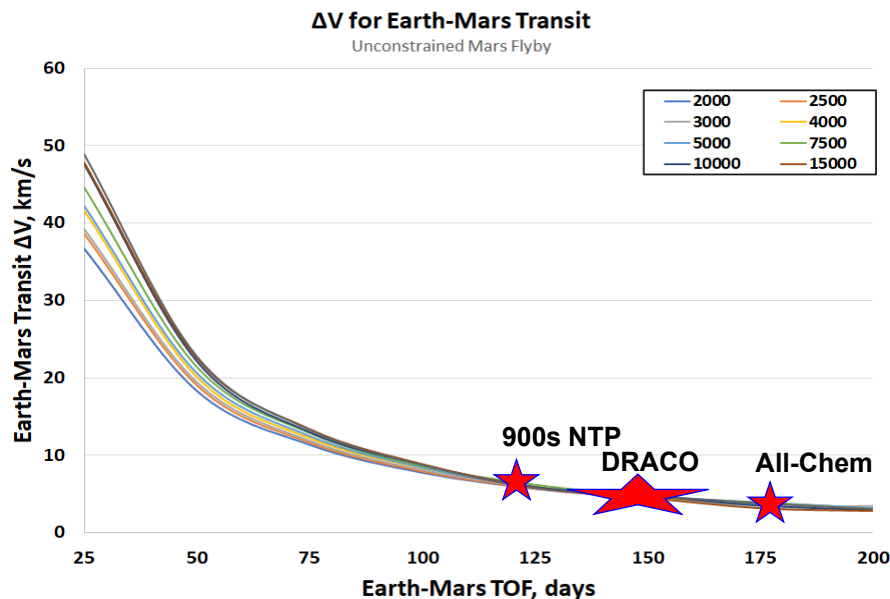
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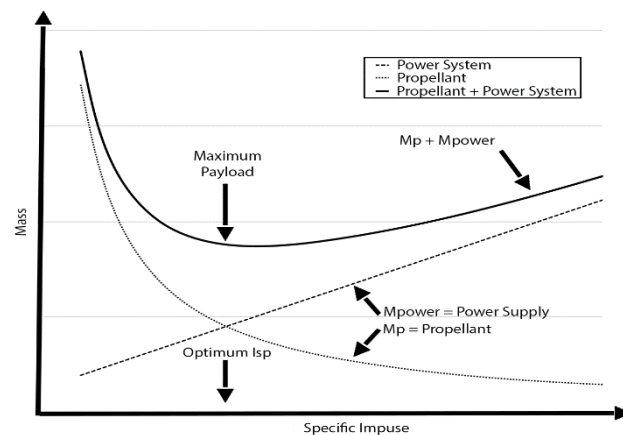
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Performance Drivers



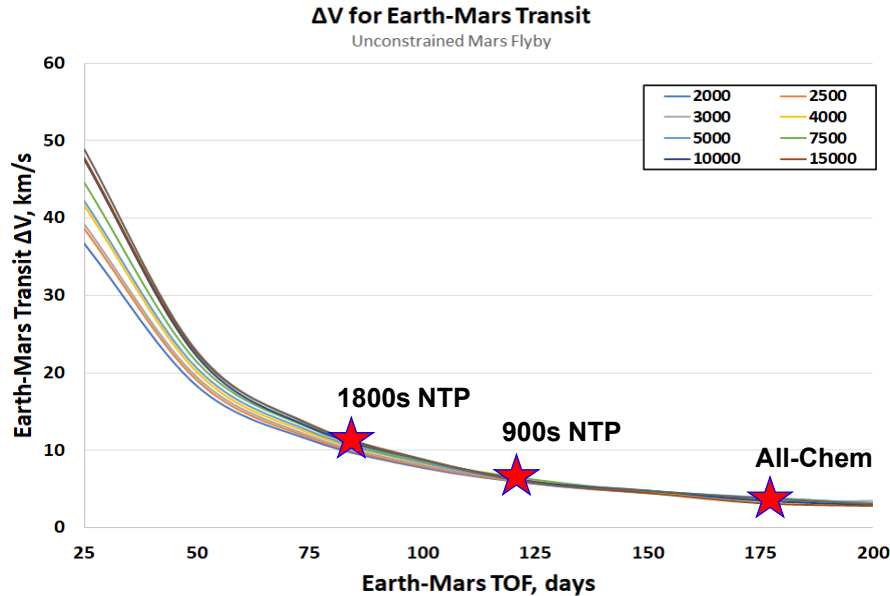
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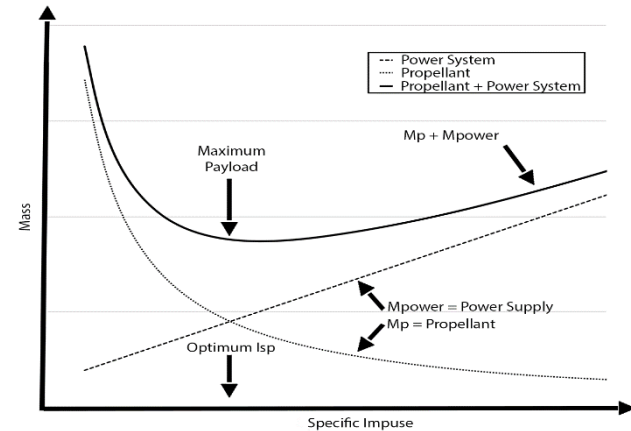
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Performance Drivers



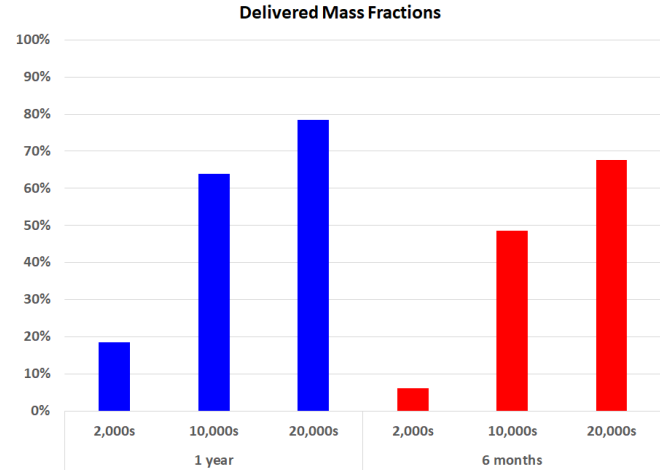
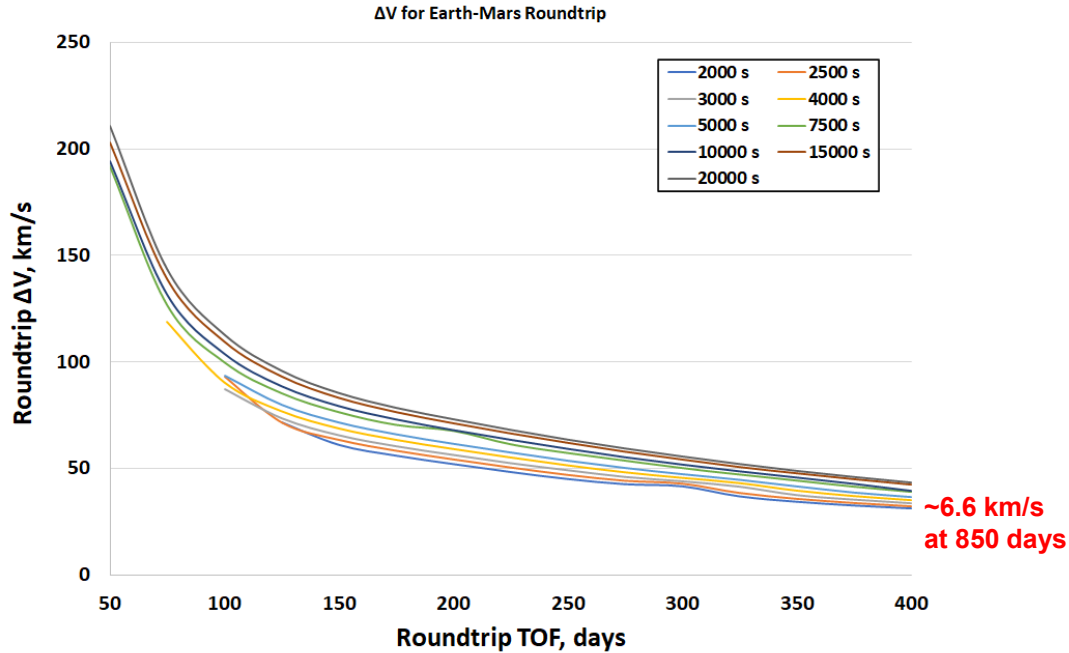
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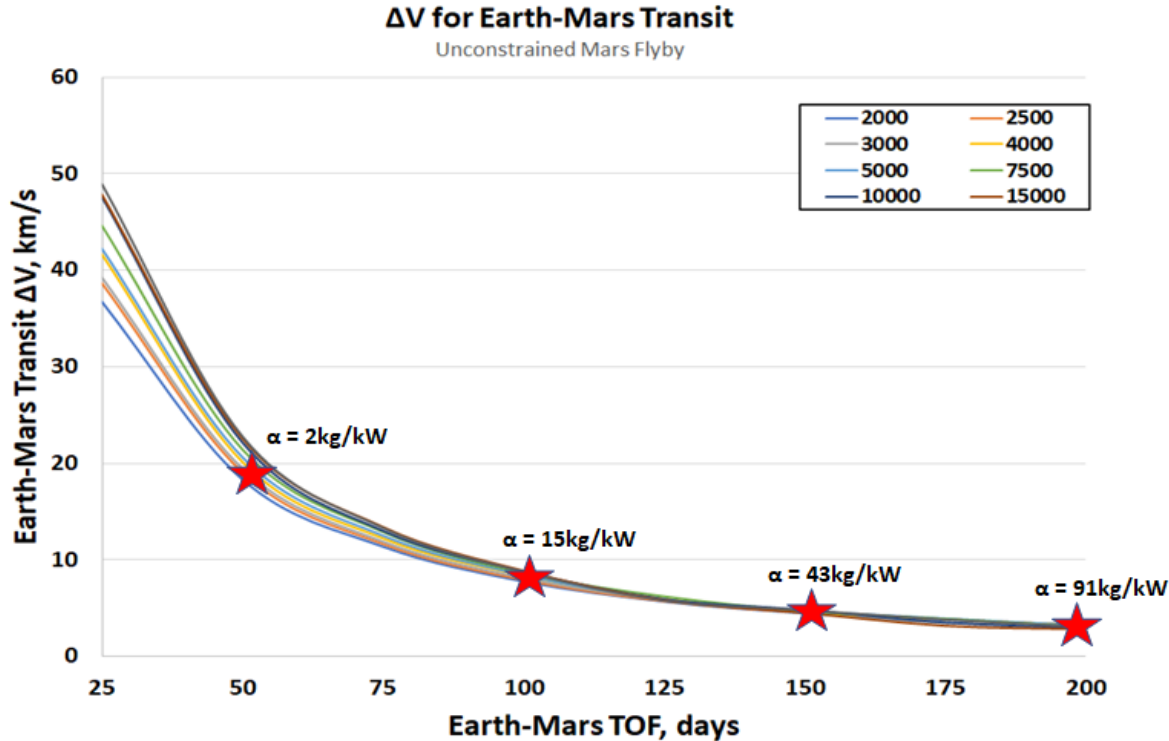
Cannot tolerate a ΔV increase faster than Specific Impulse.
 α_{System} (Kg/kWe) drives the limiting performance.

Performance Drivers



Roundtrip ΔV rises quickly for rapid transits.

Performance Drivers



α_{System} (Kg/kWe) drives the limiting performance.

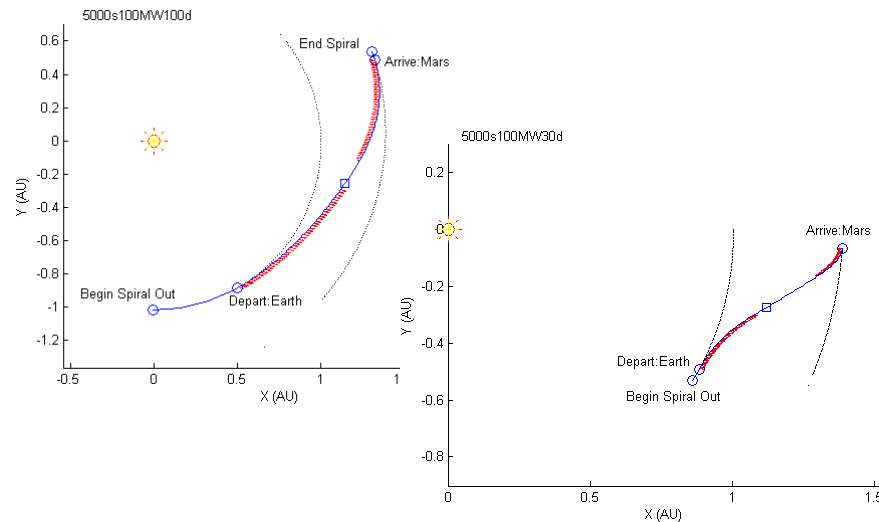
Old Study

$\eta = 80\%$

	$\alpha_{\text{Subsystems}} = 0$					$\text{MF}_{\text{Subsystems}} = 0\%$					
	2	3	4	5	6	7	8	9	10	Variable	
200	89.18	66.77	53.09	43.99	37.52	32.71	28.98	26.01	23.60	91.20	
150	42.97	33.29	26.94	22.55	19.38	16.97	15.10	13.59	12.36	43.20	
100	14.53	12.08	10.13	8.67	7.56	6.69	6.00	5.43	4.96	14.88	
50	1.81	1.87	1.74	1.59	1.45	1.33	1.22	1.12	1.04	2.32	
40	0.82	0.95	0.94	0.89	0.83	0.77	0.71	0.66	0.62	1.25	
30	0.25	0.36	0.40	0.40	0.38	0.37	0.35	0.33	0.31	0.55	
25	0.11	0.19	0.22	0.23	0.23	0.22	0.22	0.21	0.20	0.33	

$$\alpha_{\text{Payload}} = \alpha_{\text{Delivered}} - \text{MF}_{\text{Subsystems}} * (\alpha_{\text{Delivered}} / \text{MF}_{\text{Delivered}}) - \alpha_{\text{Subsystems}}$$

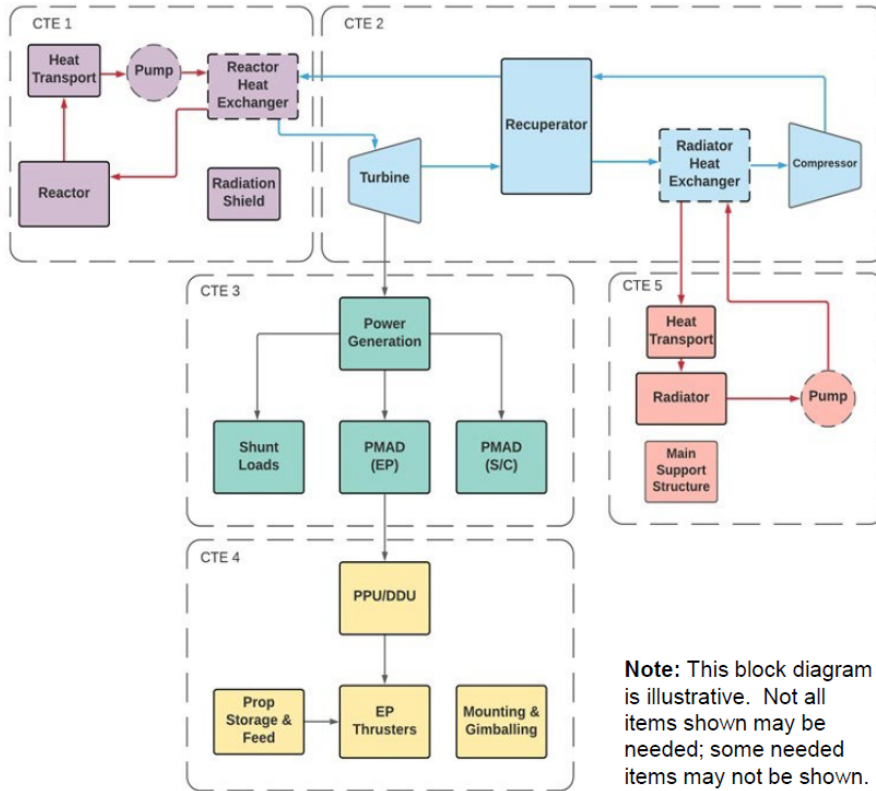
$$P_{\text{Required}} = M_{\text{Payload}} / \alpha_{\text{Payload}}$$



Dankanich and Ilin, AIAA 2010-6771

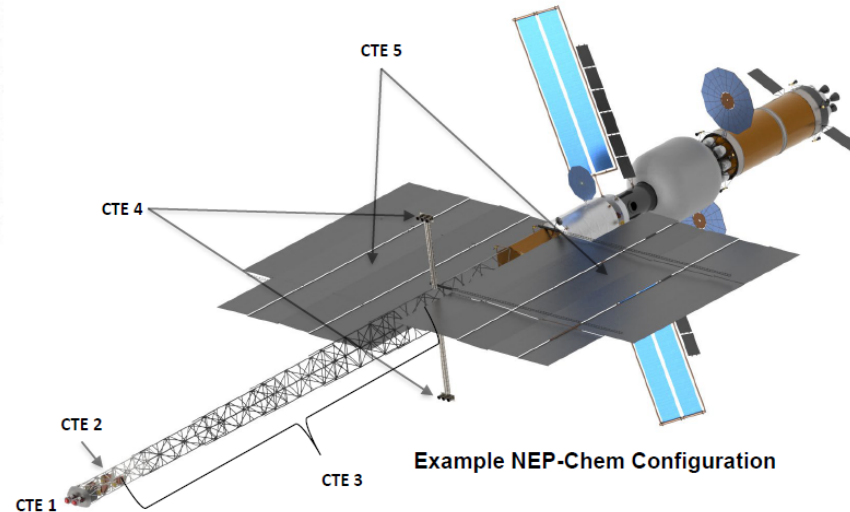
Methods were created to determine feasibility with medium fidelity optimization.

Critical Technology Elements



NEP uses heat from a nuclear reactor to produce electricity that powers electric thrusters. The NEP system has been categorized into five Critical Technology Elements (CTEs):

- CTE 1: Reactor and Coolant Subsystem (RXS)
- CTE 2: Power Conversion Subsystem (PCS)
- CTE 3: Power Management & Distribution (PMAD) Subsystem
- CTE 4: Electric Propulsion Subsystem (EPS)
- CTE 5: Primary Heat Rejection Subsystem (PHRS)



Critical Technology Elements - Planned

Subsystem	SOA	Near Term	Mid-Term
CTE-1: Power Generation	16.5	6	4.5
CTE-2: Power Conversion	10	3	2
CTE-3: PMAD	6	4	2
CTE-4: Propulsion	5.5	5	2
CTE-5: Heat Rejection (w/o deployment mechanisms)	22 (13)	(6)	(2.5)
Total System, kg/kWe	51	24	13

The current NEP TMP has significant progress potential, especially for power generation and heat rejection systems.

NEP Power Generation and Conversion

Chang Diaz, F. R., IAC 2002

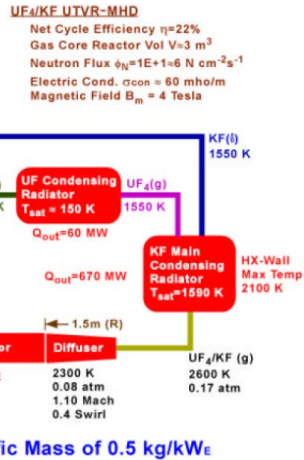


Figure 1: Ultrahigh temperature, vapor core reactor with MHD energy conversion in a closed Rankine cycle. Design by the Innovative Nuclear Space Power and Propulsion Institute of the University of Florida.

**39 Days to Mars (131 day return) plausible
with System Alpha < 1 kg/kWe**

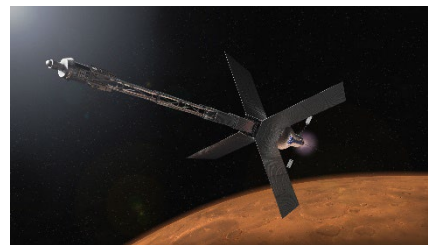
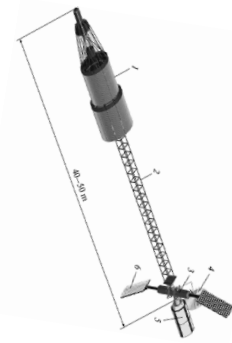
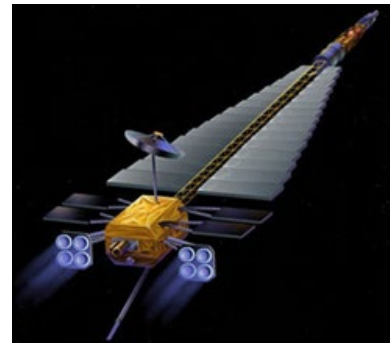
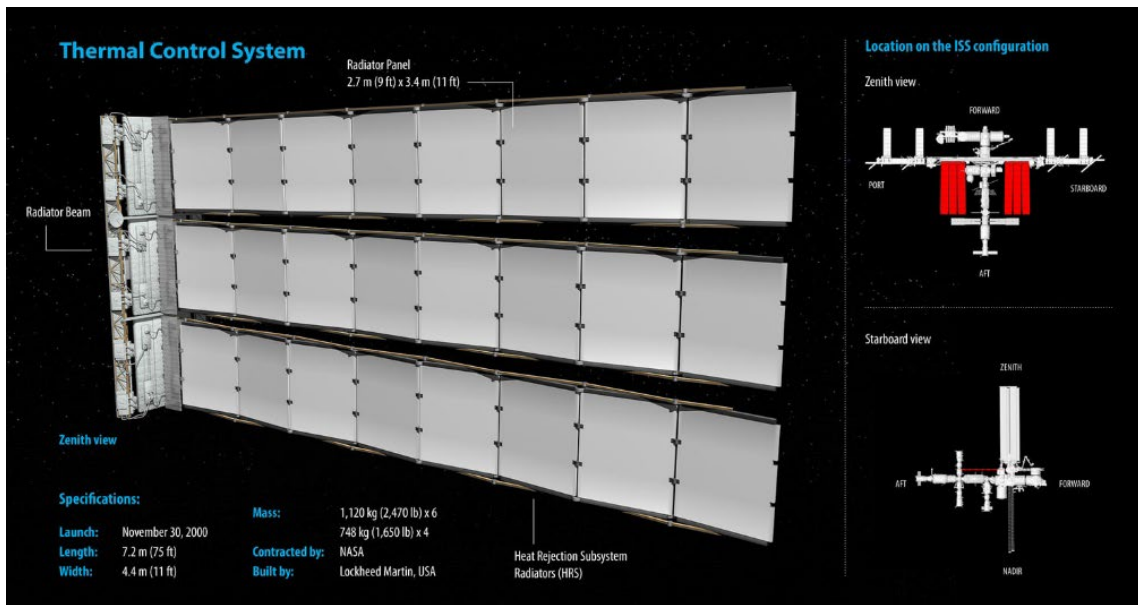
TABLE 1. Figures of Merit η and α for Advanced Electric Power and Propulsion Subsystems.

Subsystem: Technology	α	η	Reference
Energy Source: Photovoltaic Array	7.5 kg/kW _{out}	-	Donahue 2010, NREL 2012
Energy Source: Solid Core Fission	0.15 kg/kW _{out}	-	George 1991
Energy Source: Vapor Core Fission	0.05 kg/kW _{out}	-	Knight 2004
Energy Source: "Thin Core Fission"	0.15 kg/kW _{out}	-	Author estimate
Energy Source: Aneutronic Fusion	0.2 kg/kW _{out}	-	Author estimate
Energy Conversion: Rankine heat engine	0.14 kg/kW _{in}	0.18	George 1991
Energy Conversion: MHD	0.07 kg/kW _{in}	0.20	Knight 2004
Energy Conversion: TWDEC	0.14 kg/kW _{in}	0.70	Momota 1992

Scott, John H. et al., NETS 2013

**A very low mass power generation and conversion solution is required.
Multiple options have been conceived.**

NEP: Heat Rejection

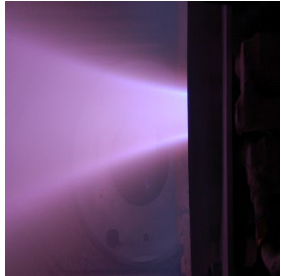


SOA Heat Rejection ~300k improves vastly with higher temperature (600k) heat rejection; 10X
Another 10x at 1500K plausible
Advanced concepts: Liquid Droplet Radiators, Belt radiators, Curie Point Radiator, etc.
Transformational: Dual purpose structural oscillating heat-pipes

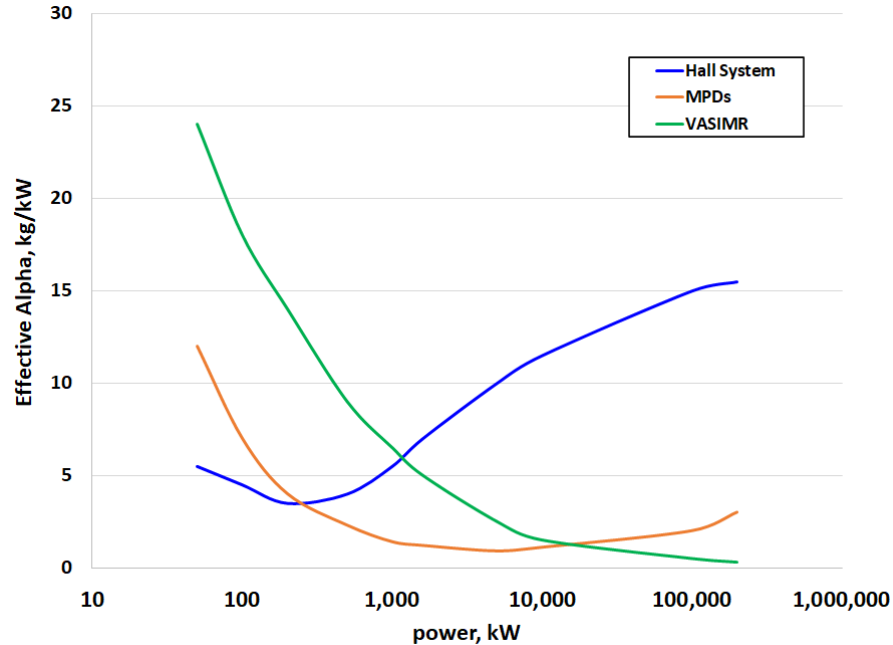
Deployment /
Structural mass
becomes limiting
factor

There is a path to ~0 kg/kW heat rejection with ROI for interim progress.

Propulsion System Options



Multiple options available for the propulsion system.



Open work to add fidelity.
e.g. We have COMPASS for Hall and VASIMR, but not MPDs

Critical Technology Elements – Far Term vs. Transformational

Subsystem	SOA	Far-Term Evolutionary	Transformative
CTE-1: Power Generation	16.5	1	0.05
CTE-2: Power Conversion	10	0.9	0.35
CTE-3: PMAD	6	2	0.07
CTE-4: Propulsion	5.5	2	0.5
CTE-5: Heat Rejection (w/o deployment mechanisms)	22 (13)	1	0
Total System, kg/kWe	51	7	0.97

Evolutionary approaches have limited potential.

Solar Power

SOA Technology

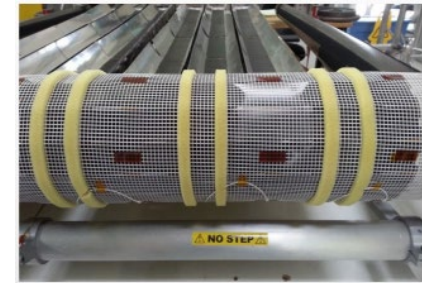
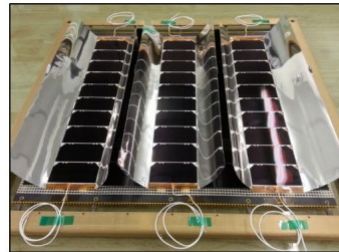
Solar Array	Power, W	Alpha, kg/kW
Rigid Panel Small (Hypothetical)	6,000	22.73
Rigid Panel Mid	25,000	12.50
Flexible fold-out	120,000	6.67
Flexible Roll Out Small (Hypothetical)	6,000	4.85
Flexible Roll-out Mid	25,000	6.67
ISS ROSA	34,000	13
Ultraflex Array (Hypothetical)	6,000	5.71
Lucy (Ultra Flex)	21,000	11.43
Insight (Ultra Flex)	1,840	10.65
Psyche	17,000	11.53

Speculative Power Sails

Solar Array	Power, W	Alpha, kg/kW
Cruiser PowerSail Moderate	774,933	0.94
Cruiser PowerSail Aggressive	1,041,788	0.45
Early Mars Crewed PowerSail	14,131,000	0.35

Evolutionary: ~Low-risk 10-year Horizon

Solar Array	Power, W	Alpha, kg/kW
MegaFlex SEP Tug	300,000	5.20 - 6.45
MegaFlex Aggressive	10,000	3.80
ROSA/FACT	25,000	3.50 - 4.40
ROSA Evolved	242,000	3.40
Compact Telescoping Array	100,000	5.40
O'Neil Fresnel Array (small)	21,1000	1.52 - 1.90
O'Neil Fresnel Array (large)	321,400	4.1 - 5.00
Scout PowerSail Conservative	29,559	1.61
Scout PowerSail Moderate	26,645	0.89
JAXA OKEANOS Power Sail	108,254	0.84 - 1.30



Redwire Solar Array FACT Flysheet, 2021

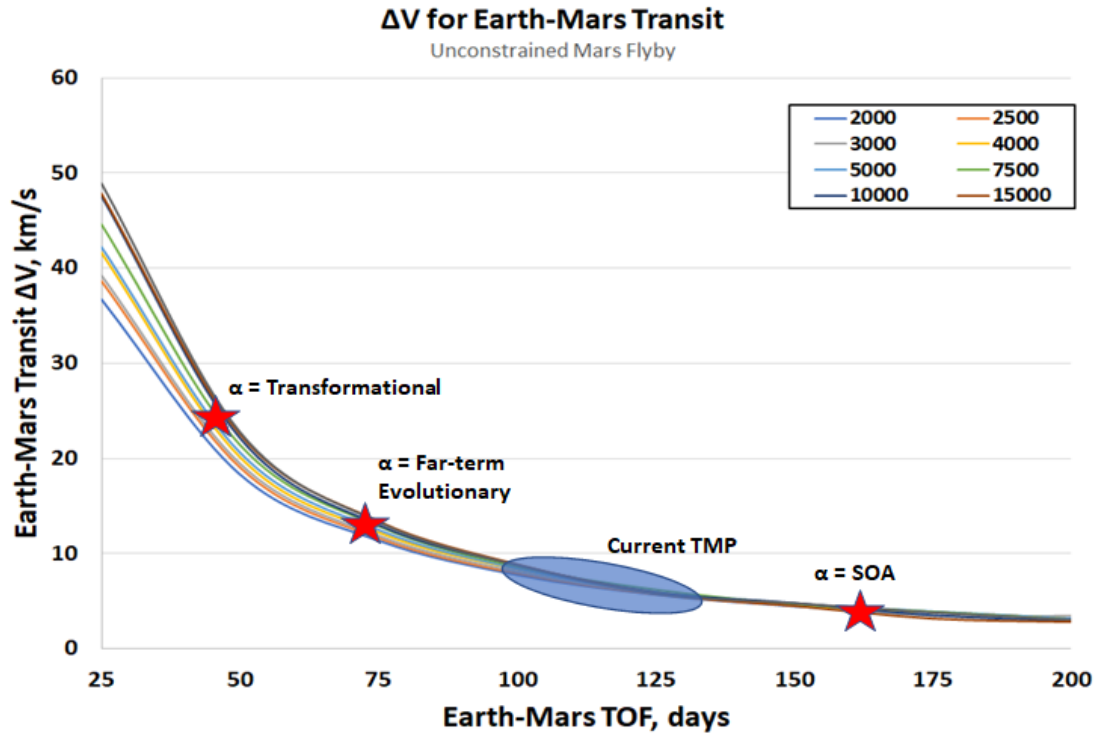
Solar Power is Very Promising; especially near-term ~low-risk.

Critical Technology Elements – Far Term vs. Transformational

Subsystem	SOA	Far-Term Evolutionary	Transformative
CTE-1: Power Generation	6.67	0.84	0.35
CTE-2: Power Conversion	-	-	-
CTE-3: PMAD	2	2	0.07
CTE-4: Propulsion	5.5	2	0.5
CTE-5: Heat Rejection	4.4	0.2	0
Total System, kg/kWe	19	5	0.92

Solar has Comparable Potential and Far Superior Near-term Performance

Performance Plan vs. Potential



Investments are Required Beyond Evolutionary Approaches

Nuclear Pulsed / Other

Non-extensive list:

- **Orion: Pulsed nuclear detonation with pusher plate.**
- VISTA: Laser ignition Inertial Confinement Fusion (ICF) based, 145 days roundtrip Mars (uncrewed)
- Daedalus: ICF based up to 12% speed of light; uncrewed
- Propagating Magnetic Wave Plasma Accelerator (PMWAC): Field Reversed Configuration (FRC) Fusion; thruster $\alpha = 6\text{E-}5$ kg/kW.
- Piloted Spherical Torus Nuclear Fusion Propulsion: Steady-state fusion.
- Dusty Plasma Fission Fragment Rocket Engine (FFRE): Allows heavy fission products to escape the reactor.
290-day roundtrip with 60-day stay and 170mT Lander and Habitat (DRA 5.0).
- The Fusion Driven Rocket: Magnetically driven liners imploding onto plasma targets.
- Pulsed Fission-Fusion: High current z-pinch compression of material liners onto fission-fusion fuel targets.
- Pulsed Plasma Rocket (PPR): ~150day roundtrip missions.
- **Gradient Field Imploding Linear Fusion Propulsion:** Magneto-Inertial Fusion (MIF),
Shifts from pulsed target compression to static high gradient allowing the use of superconducting field coils.
- Etc. (DOE and APRE-E investment derived, more likely to be identified through these external investments).

Wide range of transformational propulsion options with limited opportunities for maturation beyond concept studies.

Most require significant resources for meaningful progress i.e. high AD².

Results

Interplanetary Transit

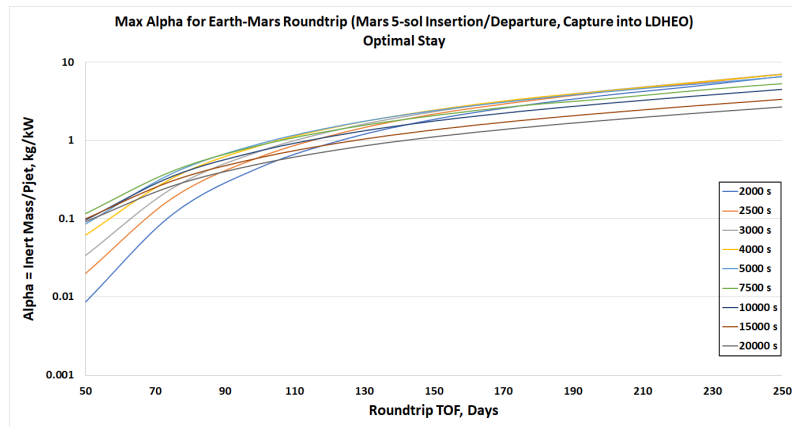
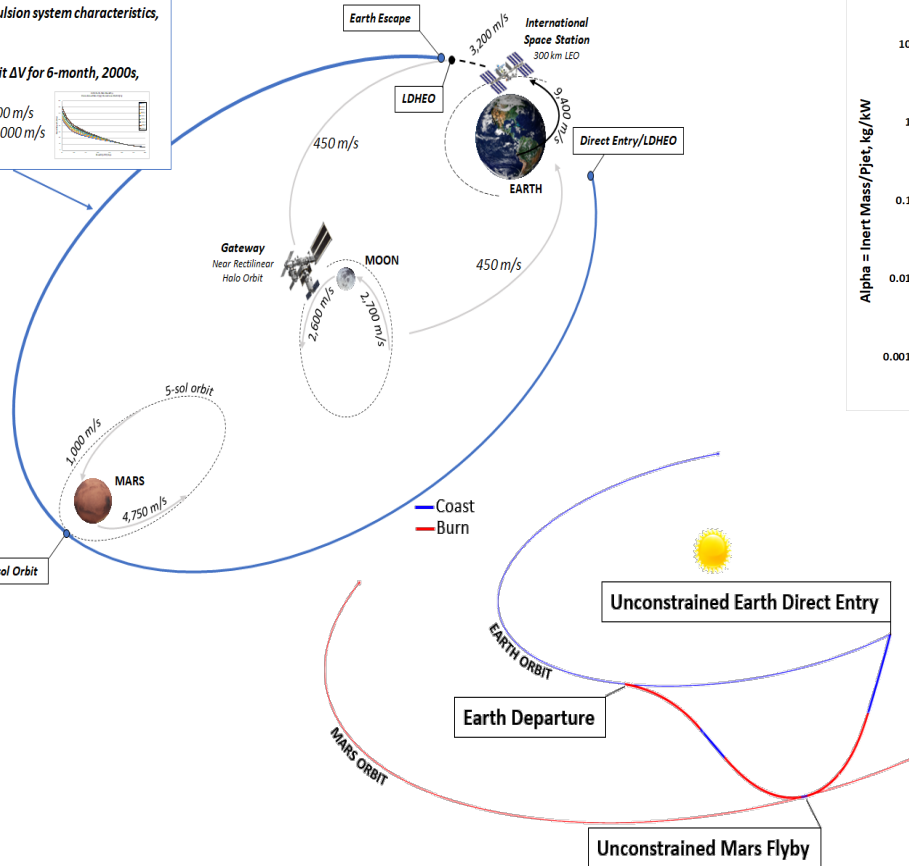
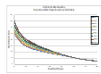
ΔV varies by transit duration, propulsion system characteristics, and Mars capture option

Example Total Interplanetary Transit ΔV for 6-month, 2000s, Optimal Stay Roundtrip Mission:

Unconstrained Flyby: 40,000–53,000 m/s

Aerocapture (6 km/s): 43,500–55,000 m/s

5-sol: 54,000–66,500 m/s



- Far-term evolutionary NEP and SEP enables roundtrip transit times of 250 days and 220 days respectively.
- Transformative performance for either NEP or SEP enables one-way and roundtrip transits of 50 days and 100 days respectively
- Viable round-trip mission less than 3 months if direct Earth entry velocities can be tolerated.



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