A GenCorp Company

Determining An Affordable Mars Mission Capable NTP Thrust Size

Nuclear And Emerging Technologies for Space (NETS) February 2015

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Non-ITAR Material – Not Export Controlled

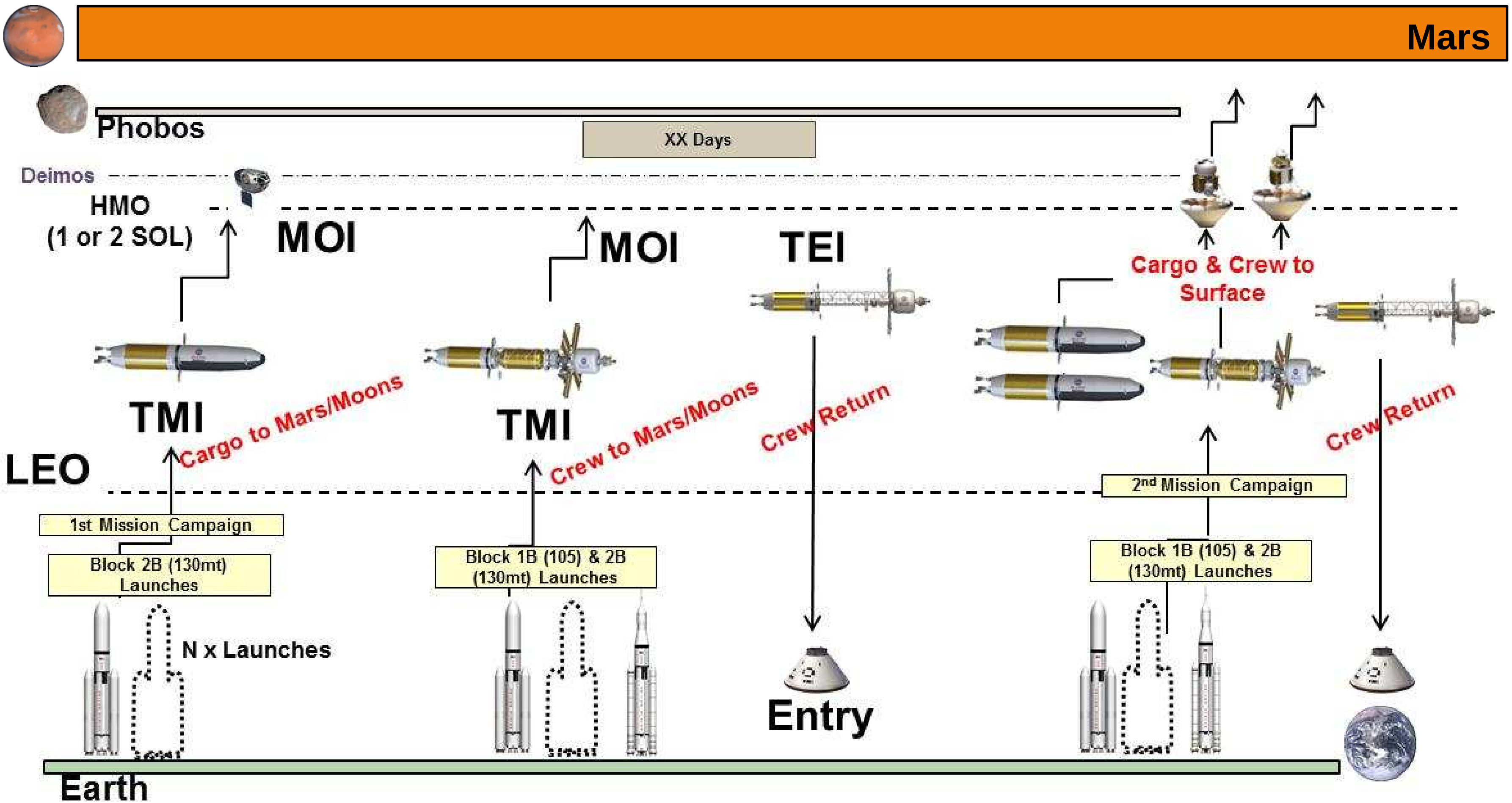
Affordable Mars Architectures

- **Goal: identify architecture and supporting technologies that enable safe, affordable human missions to Mars in the mid-2030s**
- **Focus on NTP Crew/SEP cargo architectures**
  - **Separating cargo and crew minimizes mass of crewed vehicles – enabling lower cost missions with faster crew transit times**
  - **Both SEP and NTP are established technologies – SEP is used extensively for multiple missions and NTP went thru extensive early development**
  - **NTP gives fastest transportation for crewed missions and is high TRL**
- **Affordability of NTP driven by**
  - **Thrust level (size) - smaller is better as long as performance is ok**
  - **Technology options – fuel, enrichment, and testing decisions**
  - **Development plan – minimize number of iterations**

Studies focusing on leveraging SEP cargo transportation to enable affordable NTP crew transportation

NTP=Nuclear Thermal Propulsion
SEP=Solar Electric Propulsion
TRL=Technology Readiness Level

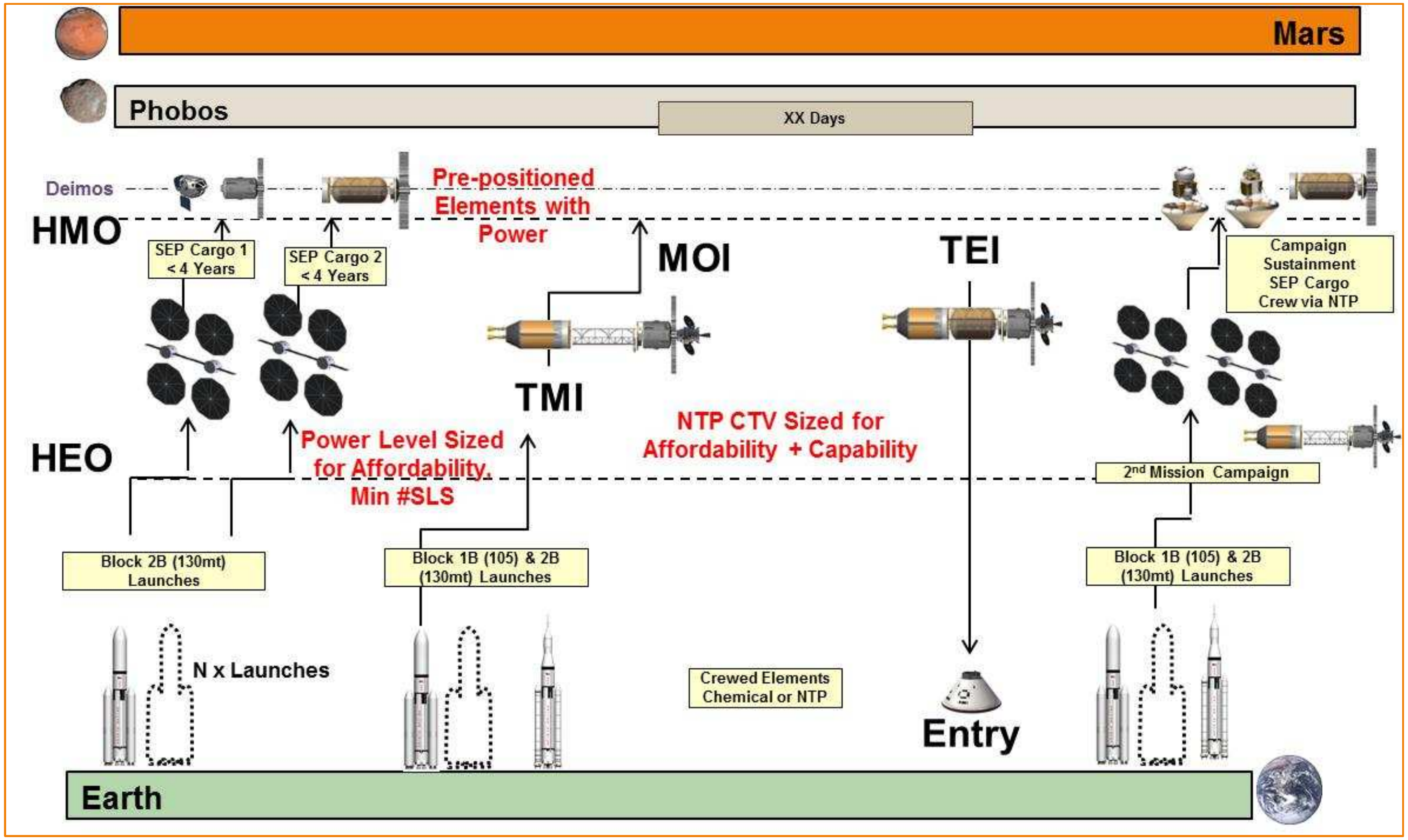
An Early Mars NTP-Only Architecture
Mars Mission Con-Ops – Conjunction Class



Typical NTP architecture reduces mass but is it affordable??

LEO=Low Earth Orbit
TMI=Trans-Mars Injection
MOC=Mars Orbit Capture
TEI=Trans-Earth Injection

A Robust Architecture for Mars and Beyond Affordability and Sustainability Via SEP+NTP



Attributes:

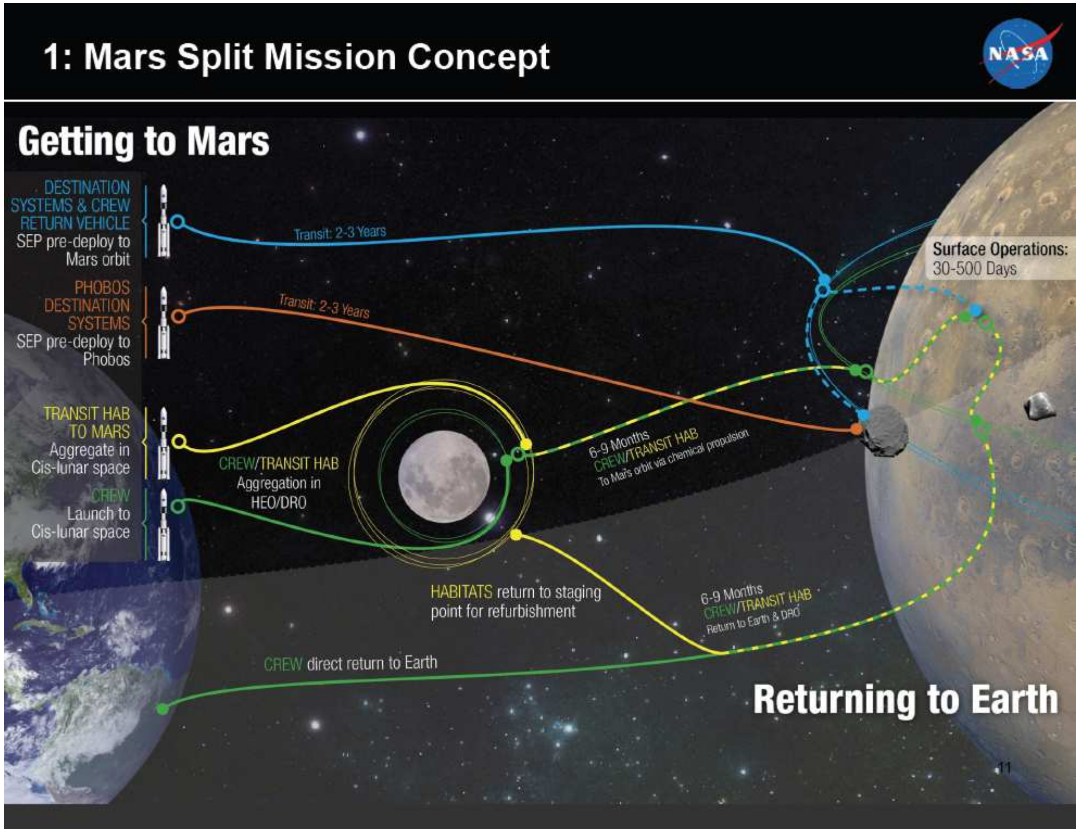
- **Evolvable: moon, Mars, asteroids, outer planets**
- **2 propulsion types for in-space transportation needs (2 baskets)**
- **Employs smaller systems (lower $)**
- **Disaggregation is sustainability (no lost $)**
- **Further refinement could use SEP cyclers: fuel, emergency, etc.**

Reduces NTP architecture size further!
Sized for affordability (Gov. & Commercial implementation) and creates sustainable round-trip architecture

HEO=High Earth Orbit
HMO=High Mars Orbit

Mars Split Architecture Mission – NASA

- **Split mission with SEP+NTP aligns with NASA's requirements and constraints**



Mars cargo and crew separation permits options for affordability - implementation per schedule & budget

So Aerojet Rocketdyne is Analyzing the SEP + NTP Evolvable Architecture Attributes

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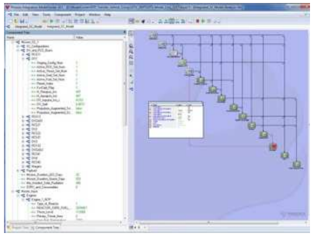
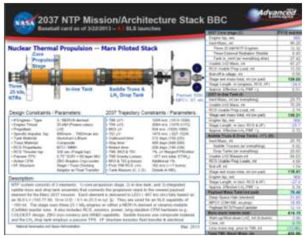
- **AR is building on past models and building new elements**
  - Always need benchmarking to align to tech assumptions
  - Benchmark 2037 Mars mission year, then across synodic cycle



- **First Study Investigated SEP Cargo and NTP Crew (CTV)**
  - SLS throws SEP (power, Isp trade for max payload) to C3 (Vinf^2)
  - NTP CTV configuration: core + in-line + drop tank anchor then vary
    - NTP T/W 3:1, Isp 900 sec
  - Look at CTV engine-out impact only for MOC & TEI burns



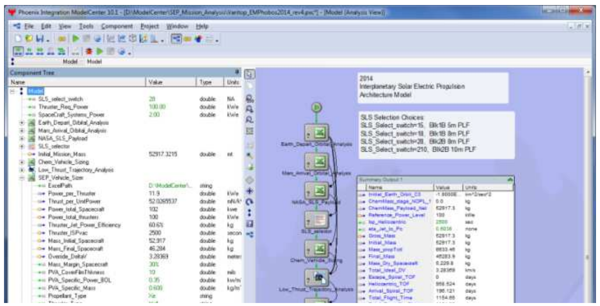
- **Used NASA MSFC/L. Kos Data (presented at NETS 2014) to anchor**
- **Used NASA Mars delta-Vs and checked AR calculations + G-losses**
- **Updated integrated models: SEP & NTP CTV**

AR architecture approach provides detailed analysis

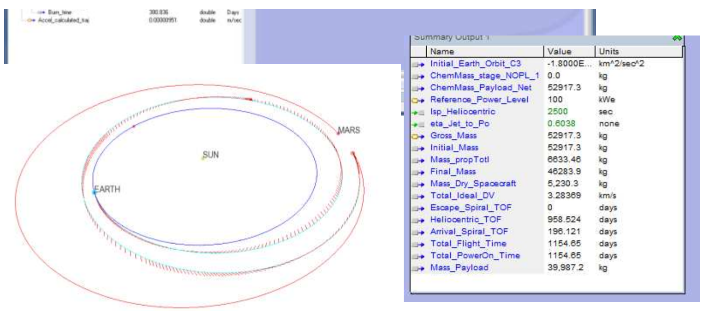
CTV=Crew Transfer Vehicle
SLS=Space Launch System

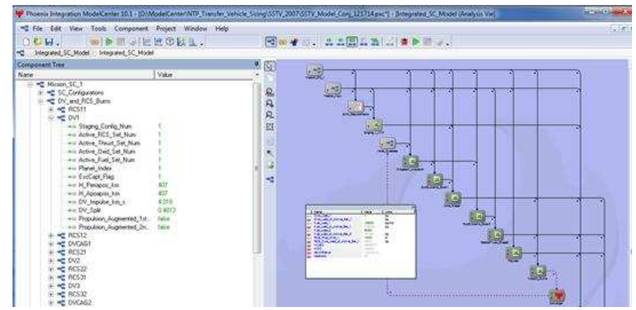
Architecture Study Using a ModelCenter SEP & NTP Sizing & Mission Models

- **Modified ModelCenter model created in 2007 for SEP and NTP analysis includes power, weights, trajectory, G-losses, boil-off, etc.**

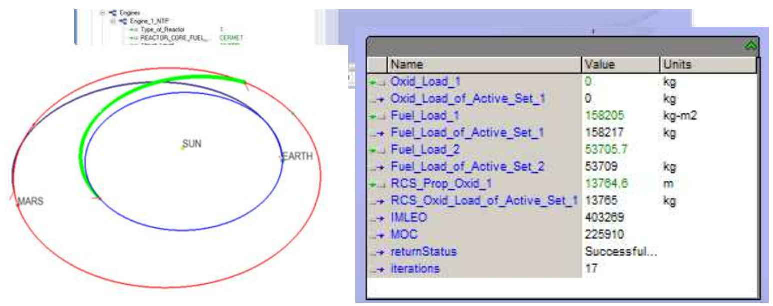


Typical SEP Cargo Summary



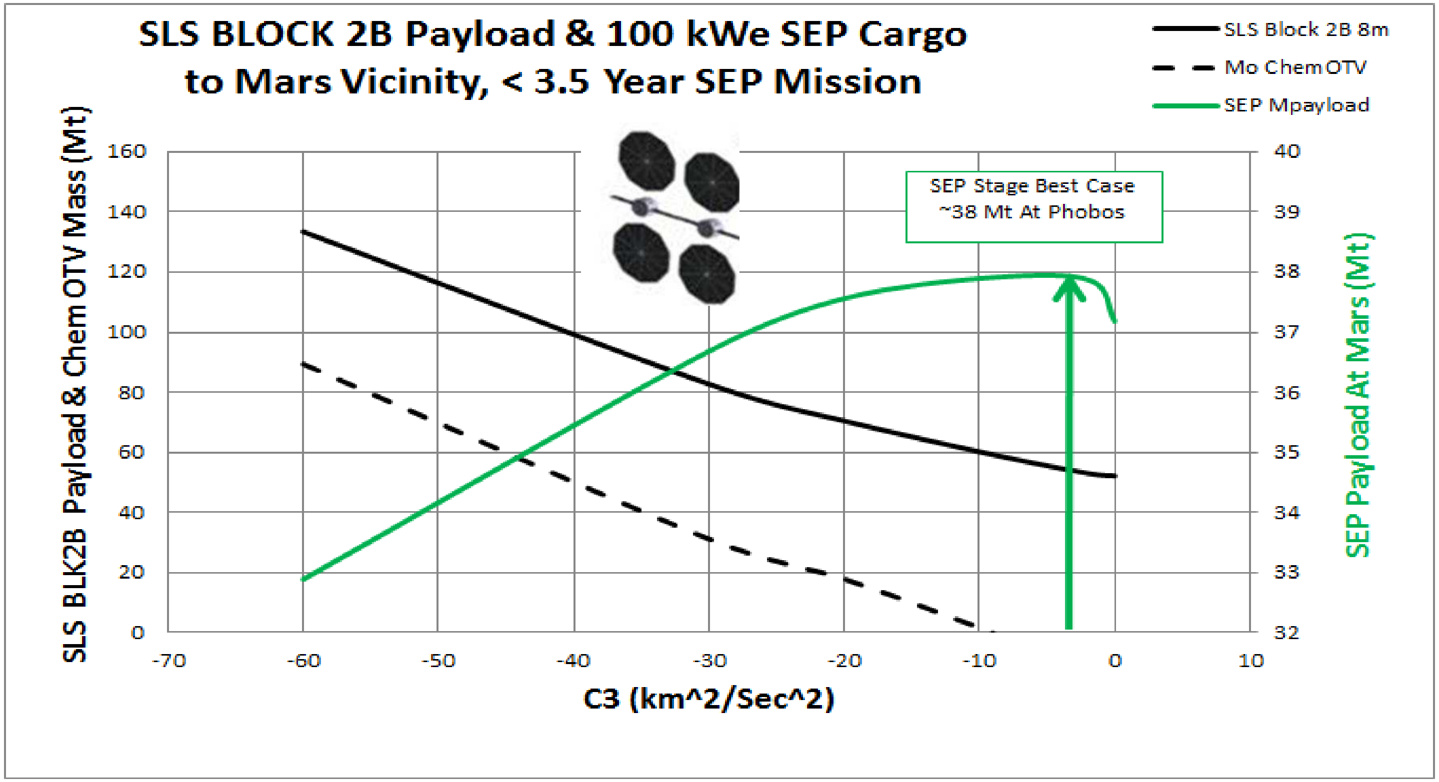


Typical NTP CTV Summary



Models are continuously improved and updated use of ModelCenter creates a robust modular framework

2028 SEP Cargo Payload Trends for SLS BLOCK 2B 8m PLF

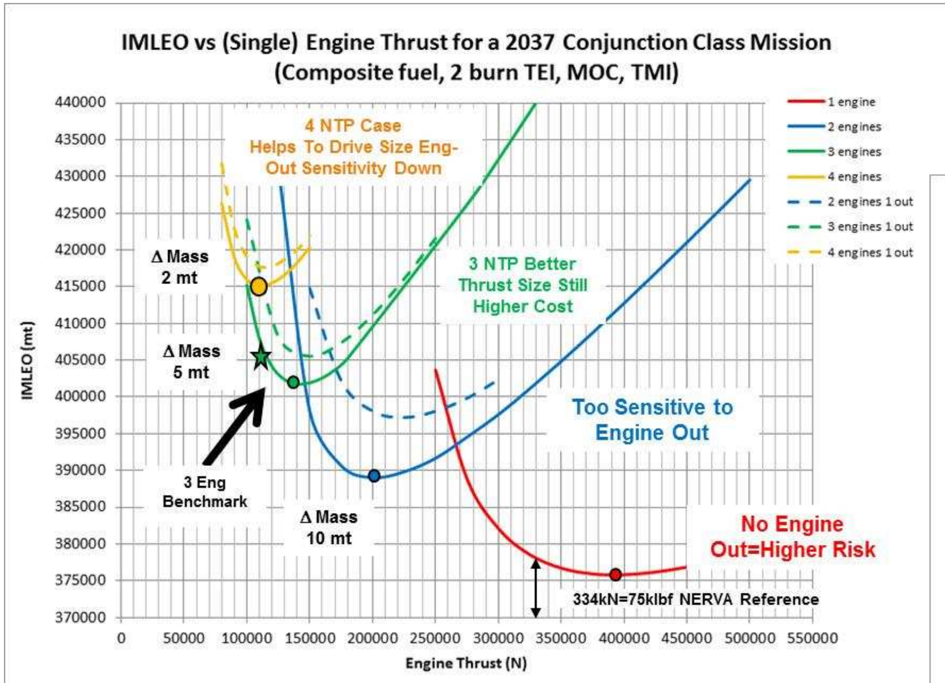


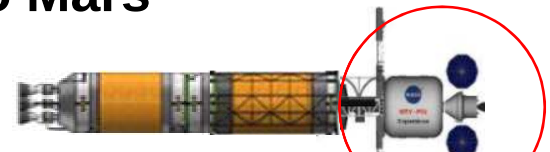
Maximum payload ~38 mT per cargo flight – Phobos orbit

OTV=Orbital Transfer Vehicle

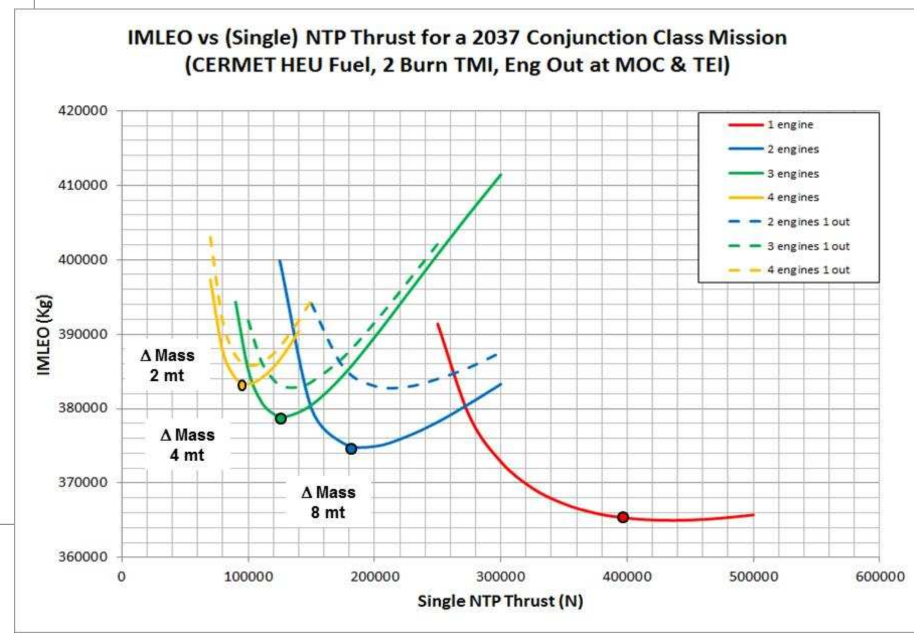
Mars CTV Architecture Trades
NTP Thrust Size Sensitivity with Engine Out

Initial assessment looked at 80mT payload to Mars





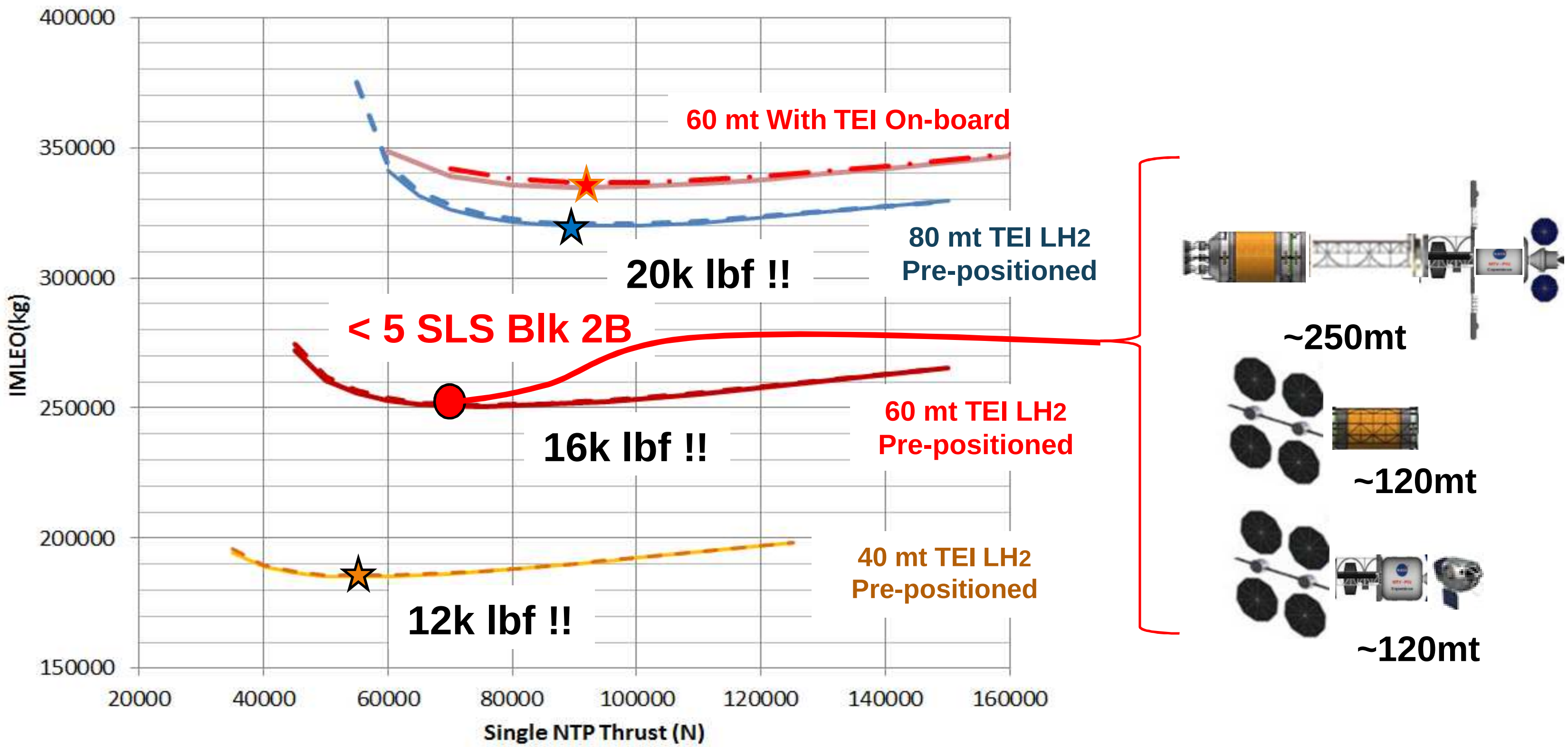
Ref: NASA



Composite & CERMET NTP systems are still large
Needing 4+ SLS's for CTV only
Payload disaggregation + split mission architecture may help

Mars SEP+NTP Architectures – Need a Paradigm

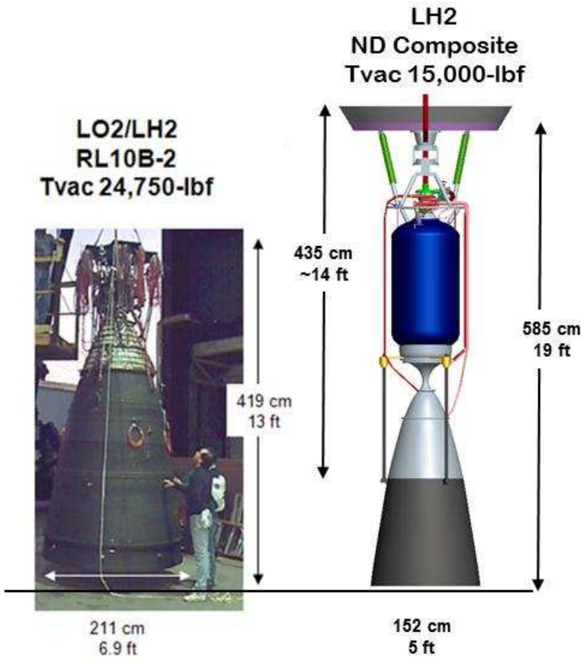
- Thrust size reduces as CTV (NTP Vehicle) size reduces (4xNTP shown)
- NO PENALTY for NTP engine out, SEP power ~100kWe per stage



Using SEP + NTP shrinks architecture and enables a low cost approach to both SEP & NTP propulsion

Summary

- **Disaggregated/split mission reduces size and mission risk**
  - A combined split Mars architecture (SEP ~100 KWe cargo) helps NTP affordability and helps thrust downsizing
    - NO BIG ENGINES with BIG TEST FOOTPRINTS
    - Use as much off-shelf technology as possible
  - Composite or Cermet NTP engine-out sizing for MOC/TEI is not large penalty on mission mass for multiple small NTP systems
  - Prepositioning has significant effect on NTP CTV size, NTP, and adds mission flexibility
  - Low power SEP helps mission affordability, sustainability



- **Next Steps/Effort**
  - Continue NTP design and NTP CTV sizing trades for variations in the architecture and mission approaches (e.g., None-stop return abort, Mars orbit sustainability, lunar and asteroid and other mission use)

BACKUP DATA

SLS-MNL-201 MPG Exec Overview 2-10-14

C3 = -60 km²/s²
~ 110 mt Net

C3 = -1.8 km²/s²
~ 55 mt Net

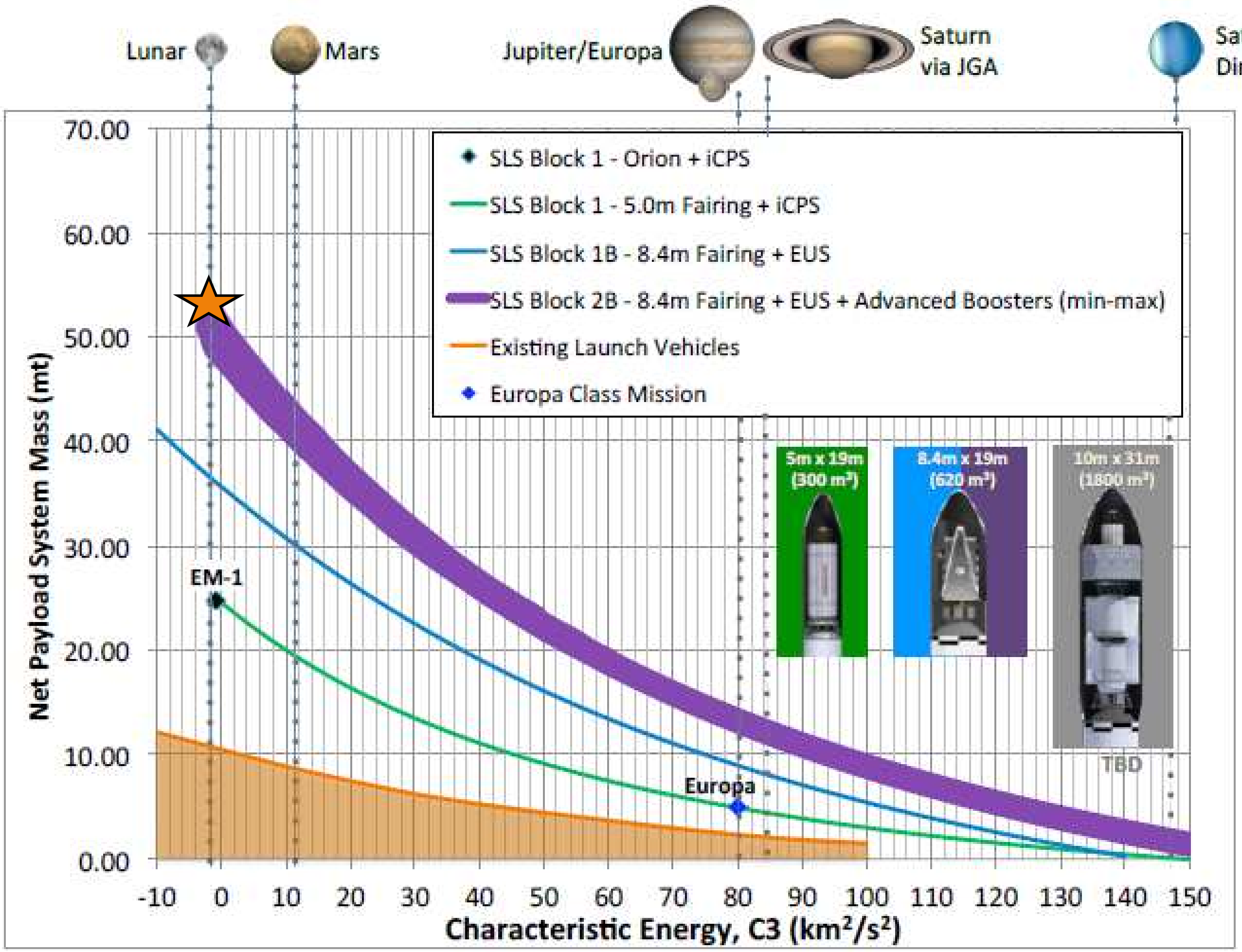
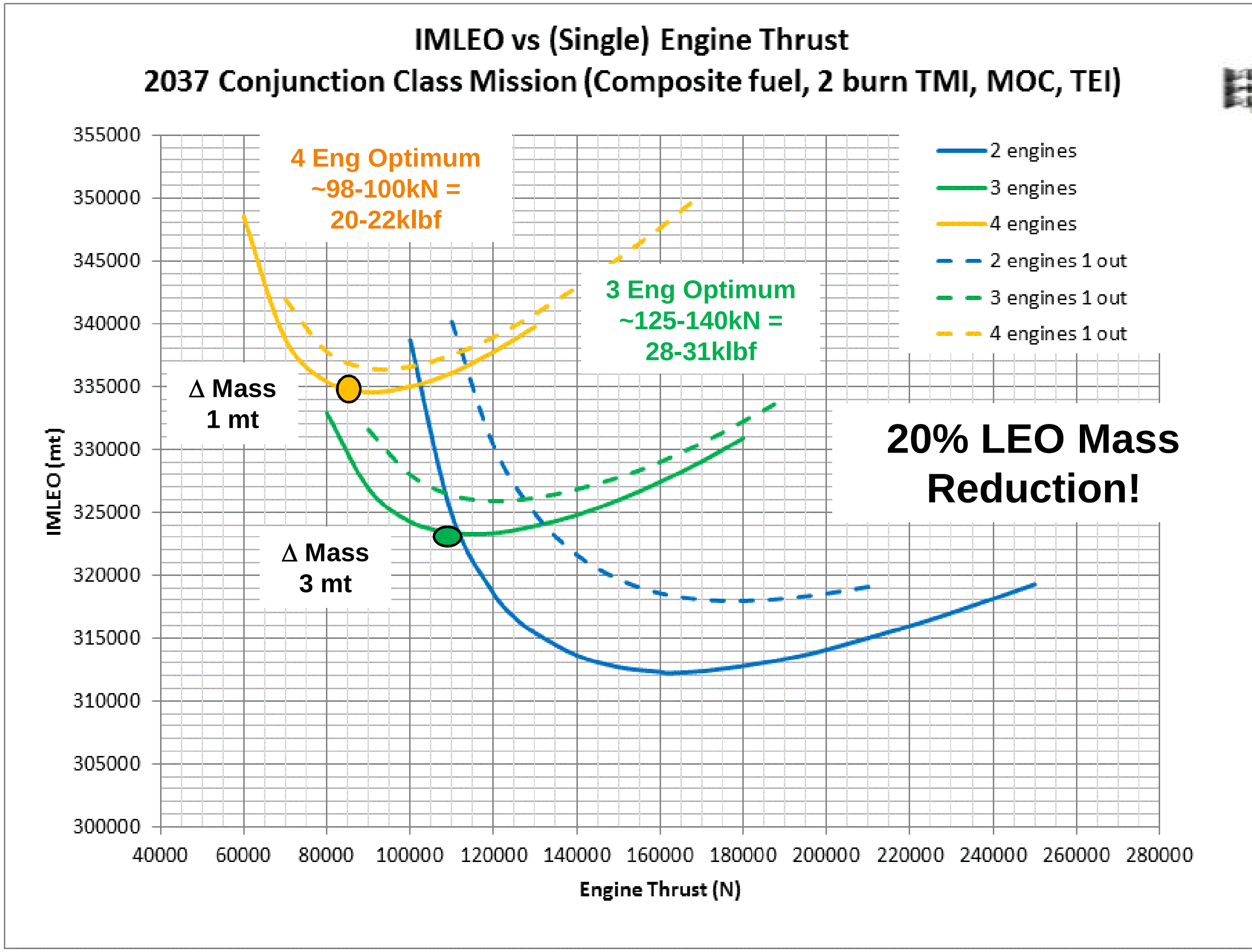
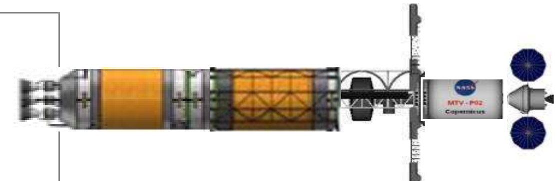


Figure 4-3. Net Payload System Mass to Earth Escape

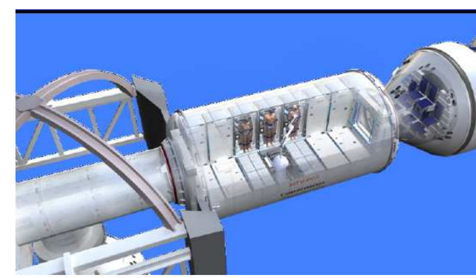
Mars CTV Trades – Example Smaller Habitat NTP Thrust Size - Graphite-Composite





Ref: NASA/AR/SEI

TOPOR*-type habitat (60 MT outbound) reduces No. of stages and consumables



*NIAC Phase 1 Grant NNX13AP82G Executive Summary, Spaceworks Engineering Inc.

"Flattens" NTP thrust size sensitivity, engine out penalty lower
Thrust size now near 16k-17k lbf

Past 2006 Study
Light Crew Habitat and Easy Opposition Mission

Older NTP and BNTP Study 2033 Opposition, TMI Eng-Out

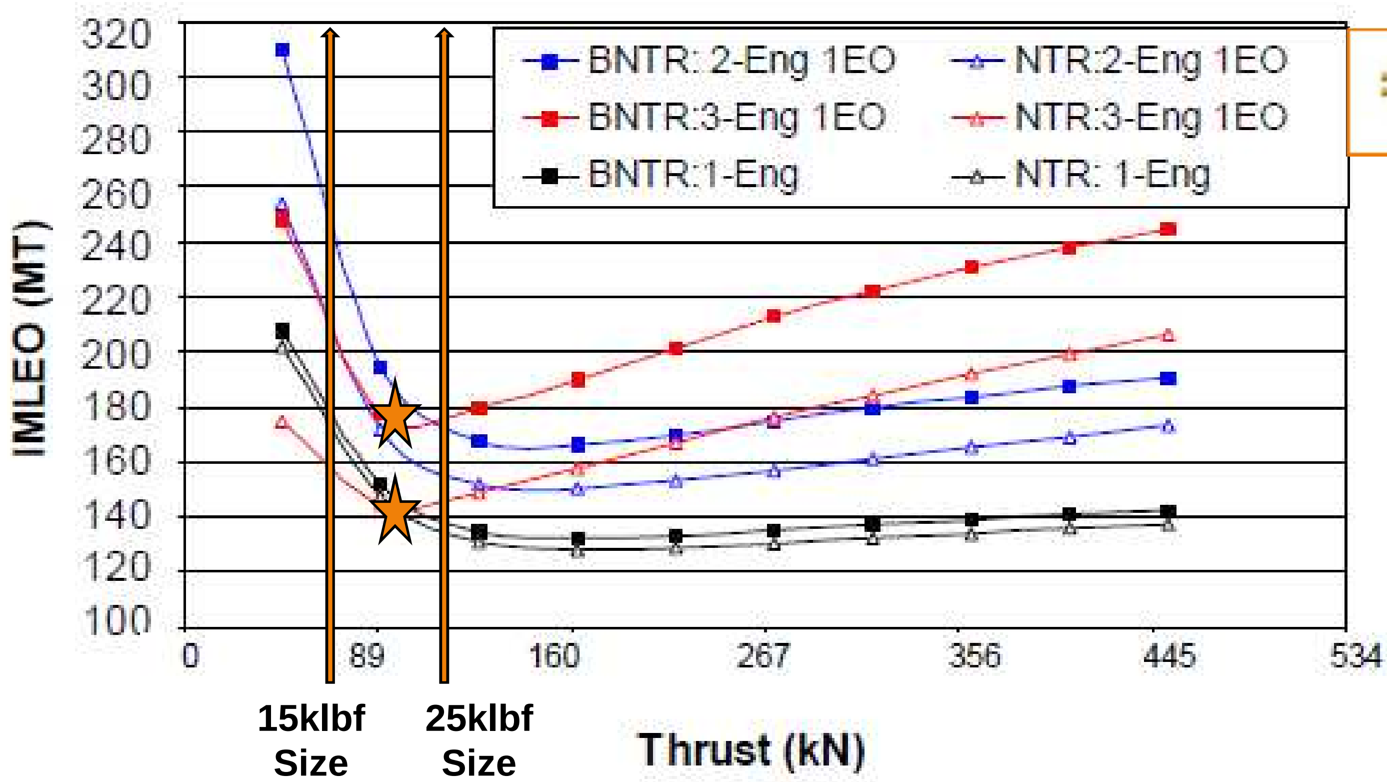
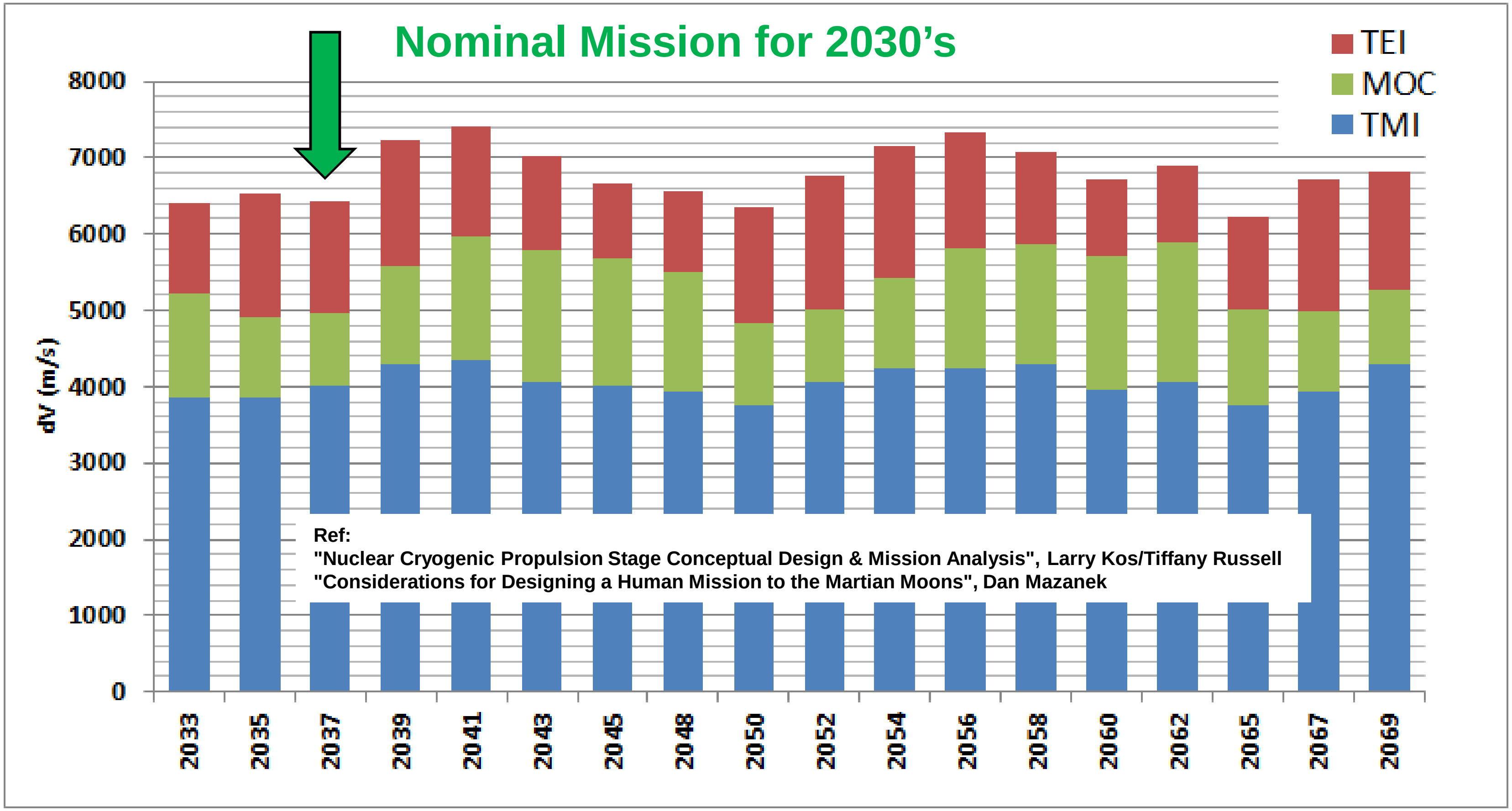


FIGURE 4. NTP, BNTP IMLEO Trends for CERMET.

(50 MT outbound)

2033 Opposition optimum thrust size 15k-20k lbf

Impulsive Delta V's – Mars Conjunction Class



So need a model benchmark case – 2037 mission year

ModelCenter CTV Model Assumptions Verification – NASA L. Kos 2037 Case

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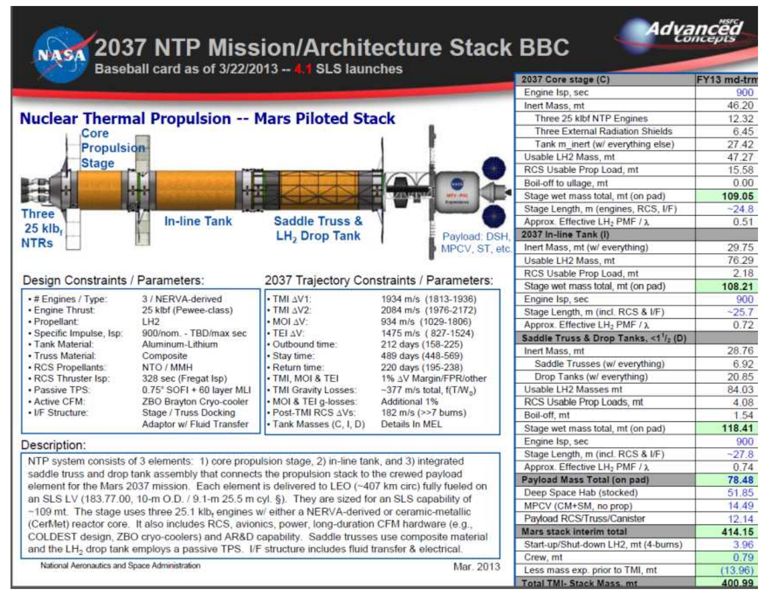
- **Relevant case from NASA activity in 2014**
- **AR mission model applied similar assumptions for this 2037 case**
- **Significant driver assumptions:**
  - 2037 Conjunction Class
    - Delta V's (2b TMI, MOC, TEI)
      - 4018, 934, 1475 m/s
  - ISP 900 sec
  - 3 x 25k-lbf Thrust NTP, T/Wntp = 2.76
  - AL-Li Tanks, 0.75"SOFI+60 Layer MLI
  - ZBO Cryo-cooler (No Core LH2 Boil Off)
  - Mission Payload 78.5 mt (52 mt LD Hab)
  - SLS Payload to 407 km 109 mt
- **IMLEO pre-TMI ~401 mt**
- **T/W pre-TMI ~ 0.085**



2037 NTP Mission/Architecture Stack BBC

Baseball card as of 3/22/2013 -- 4.1 SLS launches

MSFC Advanced Concepts

Nuclear Thermal Propulsion -- Mars Piloted Stack

Design Constraints / Parameters:

• # Engines / Type:	3 / NERVA-derived
• Engine Thrust:	25 klbf (Pewee-class)
• Propellant:	LH2
• Specific Impulse, Isp:	900/nom. - TBD/max sec
• Tank Material:	Aluminum-Lithium
• Truss Material:	Composite
• RCS Propellants:	NTO / MMH
• RCS Thruster Isp:	328 sec (Fregat Isp)
• Passive TPS:	0.75" SOFI + 60 layer MLI
• Active CFM:	ZBO Brayton Cryo-cooler
• I/F Structure:	Stage / Truss Docking Adaptor w/ Fluid Transfer

2037 Trajectory Constraints / Parameters:

• TMI ΔV1:	1934 m/s (1813-1936)
• TMI ΔV2:	2084 m/s (1976-2172)
• MOI ΔV:	934 m/s (1029-1806)
• TEI ΔV:	1475 m/s (827-1524)
• Outbound time:	212 days (158-225)
• Stay time:	489 days (448-569)
• Return time:	220 days (195-238)
• TMI, MOI & TEI	1% ΔV Margin/FPR/other
• TMI Gravity Losses:	~377 m/s total, f(T/W$_0$)
• MOI & TEI g-losses:	Additional 1%
• Post-TMI RCS ΔVs:	182 m/s (>>7 burns)
• Tank Masses (C, I, D)	Details In MEL

Description:

NTP system consists of 3 elements: 1) core propulsion stage, 2) in-line tank, and 3) integrated saddle truss and drop tank assembly that connects the propulsion stack to the crewed payload element for the Mars 2037 mission. Each element is delivered to LEO (~407 km circ) fully fueled on an SLS LV (183.77.00, 10-m O.D. / 9.1-m 25.5 m cyl. §). They are sized for an SLS capability of ~109 mt. The stage uses three 25.1 klb$_f$ engines w/ either a NERVA-derived or ceramic-metallic (CerMet) reactor core. It also includes RCS, avionics, power, long-duration CFM hardware (e.g., COLDEST design, ZBO cryo-coolers) and AR&D capability. Saddle trusses use composite material and the LH_2 drop tank employs a passive TPS. I/F structure includes fluid transfer & electrical.

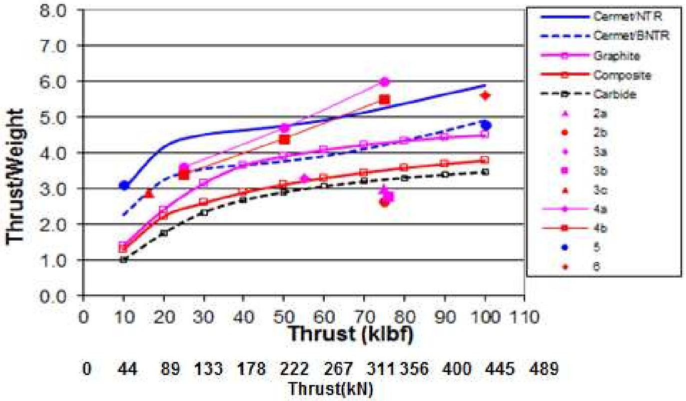
National Aeronautics and Space Administration — Mar. 2013

2037 Core stage (C)	FY13 md-trm
Engine Isp, sec	900
Inert Mass, mt	46.20
Three 25 klbf NTP Engines	12.32
Three External Radiation Shields	6.45
Tank m_inert (w/ everything else)	27.42
Usable LH2 Mass, mt	47.27
RCS Usable Prop Load, mt	15.58
Boil-off to ullage, mt	0.00
Stage wet mass total, mt (on pad)	**109.05**
Stage Length, m (engines, RCS, I/F)	~24.8
Approx. Effective LH_2 PMF / λ	0.51
2037 In-line Tank (I)	
Inert Mass, mt (w/ everything)	29.75
Usable LH2 Mass, mt	76.29
RCS Usable Prop Load, mt	2.18
Stage wet mass total, mt (on pad)	**108.21**
Engine Isp, sec	900
Stage Length, m (incl. RCS & I/F)	~25.7
Approx. Effective LH_2 PMF / λ	0.72
Saddle Truss & Drop Tanks, <1 1/2 (D)	
Inert Mass, mt	28.76
Saddle Trusses (w/ everything)	6.92
Drop Tanks (w/ everything)	20.85
Usable LH2 Masses mt	84.03
RCS Usable Prop Loads, mt	4.08
Boil-off, mt	1.54
Stage wet mass total, mt (on pad)	**118.41**
Engine Isp, sec	900
Stage Length, m (incl. RCS & I/F)	~27.8
Approx. Effective LH_2 PMF / λ	0.74
Payload Mass Total (on pad)	**78.48**
Deep Space Hab (stocked)	51.85
MPCV (CM+SM, no prop)	14.49
Payload RCS/Truss/Canister	12.14
Mars stack interim total	**414.15**
Start-up/Shut-down LH2, mt (4-burns)	3.96
Crew, mt	0.79
Less mass exp. prior to TMI, mt	(13.96)
Total TMI- Stack Mass, mt	**400.99**

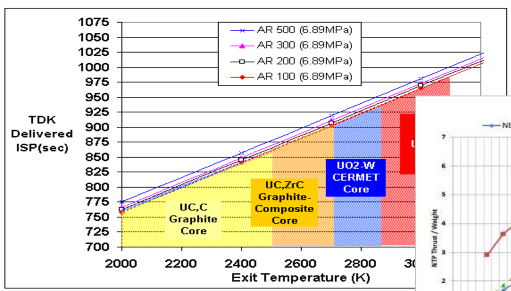
Mars 2037 mission year

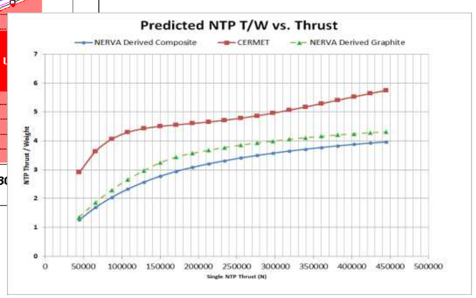
2037 Mars CTV NTP Trades
NTP Thrust to Weight Trends

Legacy Design Data

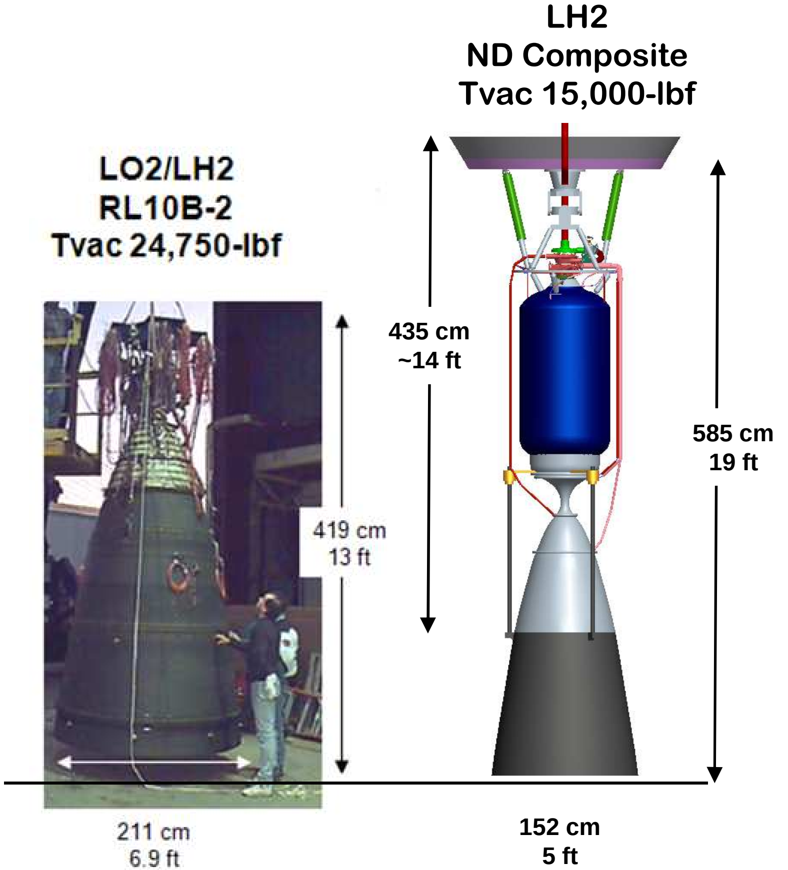


NTP Data Used in This Trade Study



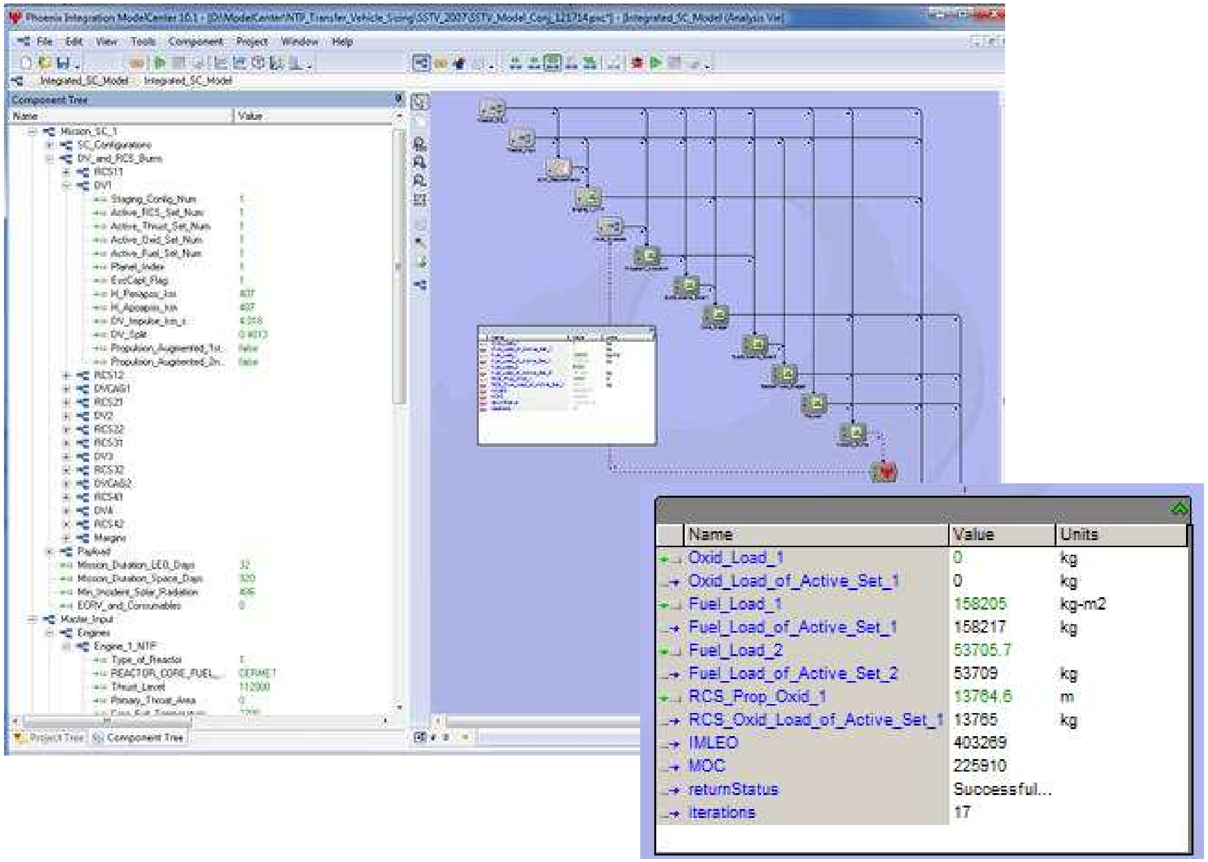


15,000 lbf ND Composite, 300:1, T/W ~3 Example

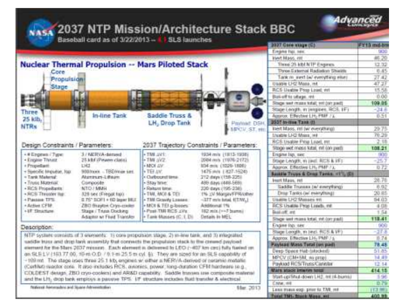


These thrust to weights include internal & external shields

ModelCenter NTP Mission Model Anchoring



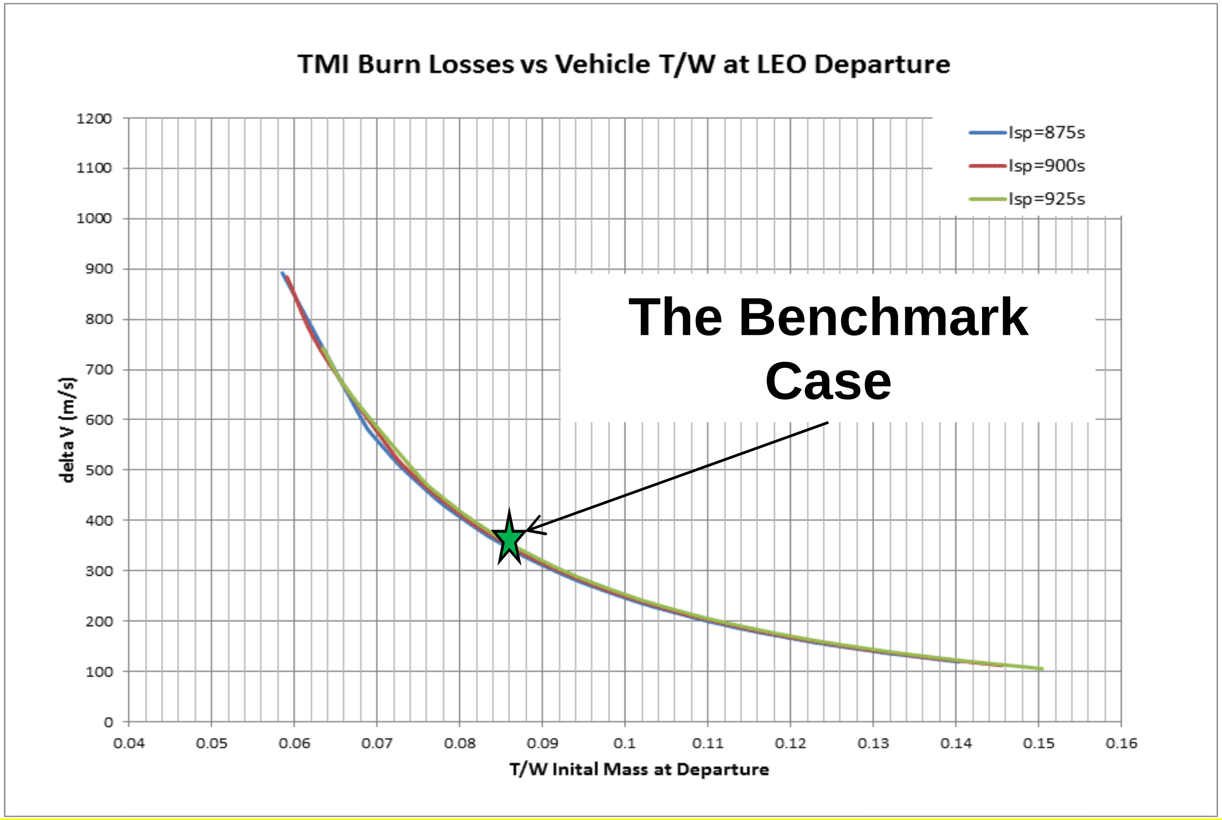
- 80 MT payload outbound, 75 MT inbound
- ConOps: 32 days in LEO, 920 In-space days (212 outbound, 489 in Mars orbit, 220 inbound)
- MPCV/consumables accounted for in secondary payload
- NTP: Composite reactor T/W, Benchmark Thrust 25.1klbf, Core temp. set for Isp=900 s



Reasonable match at 403 Mt (AR) vs. 401 Mt (NASA) for same assumptions

2037 Mars CTV Trades – G-loss

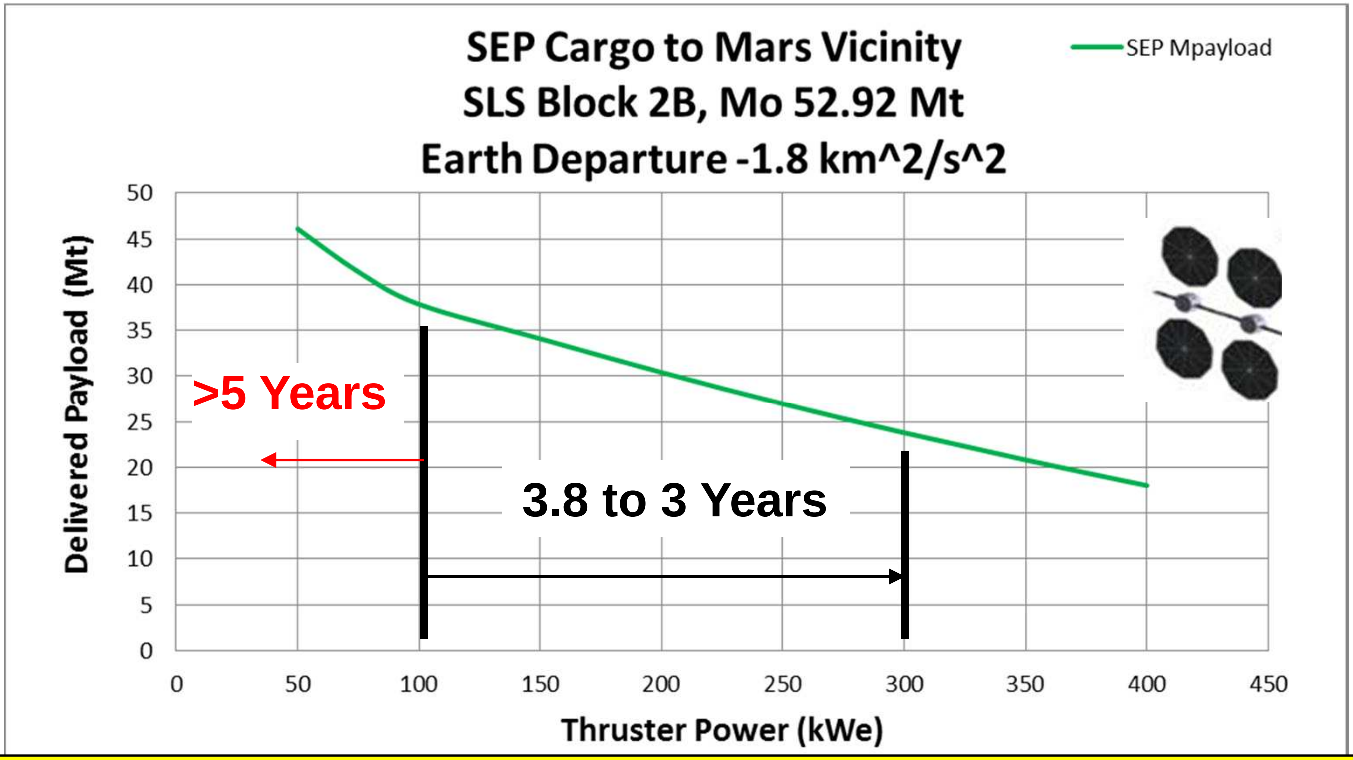
- **Gravity losses calculated for each impulsive burn as integrated equations within each gravity field**
- **Earth departure TMI losses shown here**



All burns included some gravitational losses

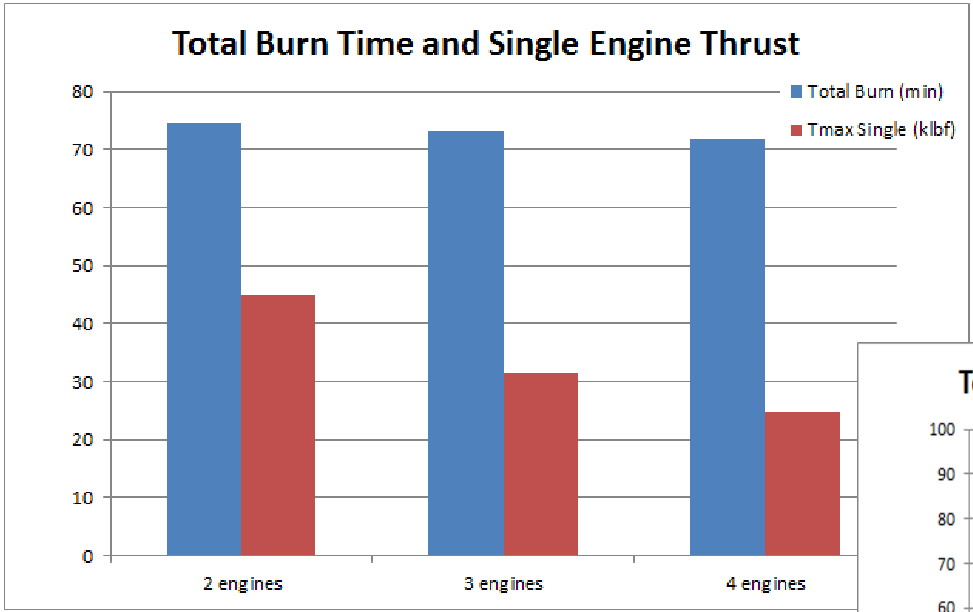
Power Trades for All Else Constant (2028)

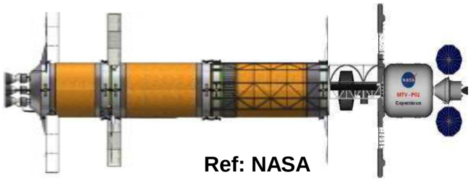
- **General Trends Indicates – do not go up In power If you want maximum cargo to Mars in (1) SLS launch from C3= -1.8 Km^2/sec^2**
  - **50 kWe trajectory and lower, $\geq$ 5 Years Flight Time**
  - **75 kWe trajectories and higher, $\leq$ 4 Years Flight Time**



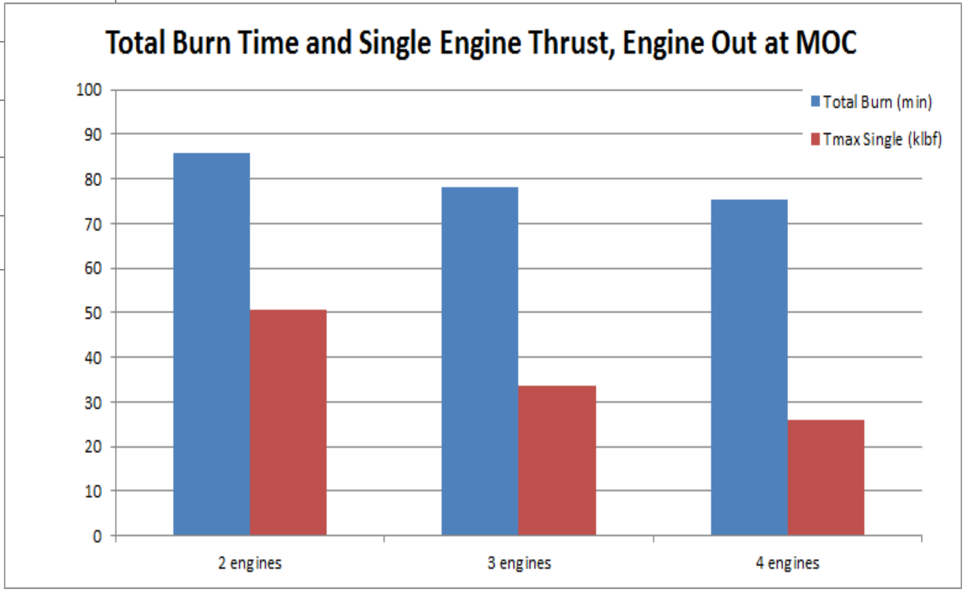
Highest payload with 100-150 KWe
Shortest travel With 300 KWe but 5-10 Mt less payload

Mars CTV Trades
Total Mission Burn Time for Composite* NTP





80 MT outbound
75 MT inbound

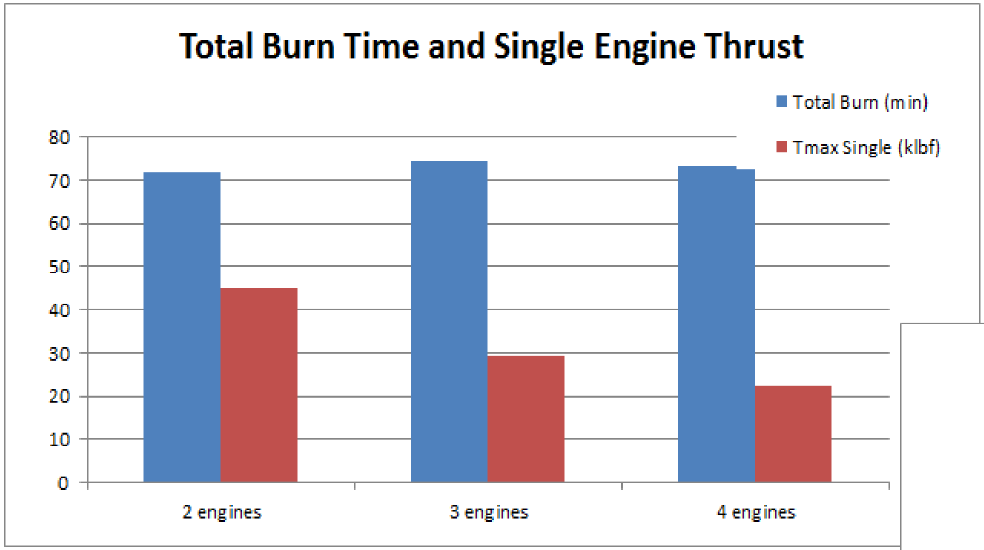


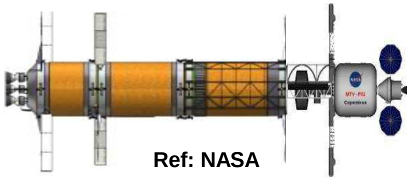
Engine out sizing adds ~10 minutes to total burn time

Three & four NTP engine cases add the least additional time

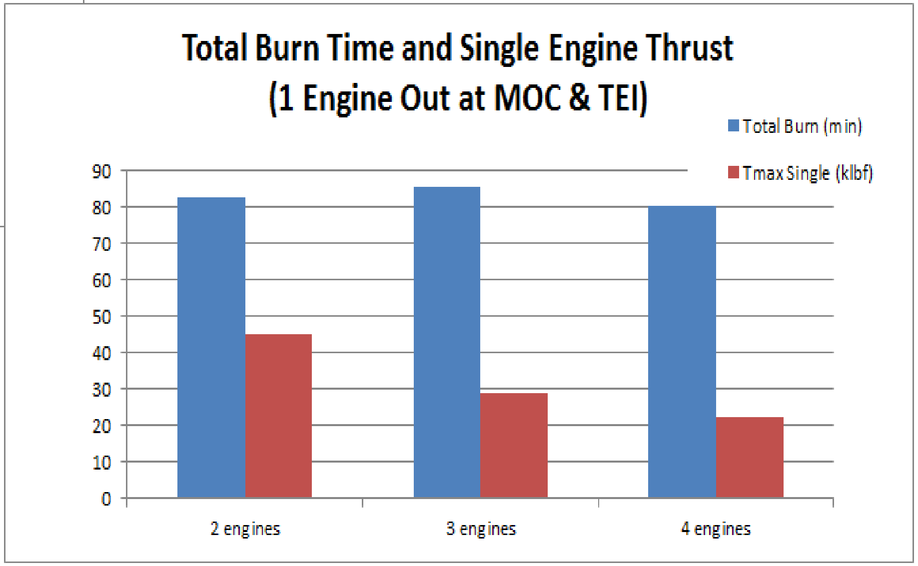
*Graphite-Composite

Mars CTV Trades
Total Mission Burn Time for Cermet NTP





80 MT outbound



Engine out sizing adds ~10 minutes to total burn time

Cermet Four NTP engine case adds the least additional time