"The Benefits of Nuclear Thermal Propulsion (NTP) in an Evolvable Mars Campaign"

presented by

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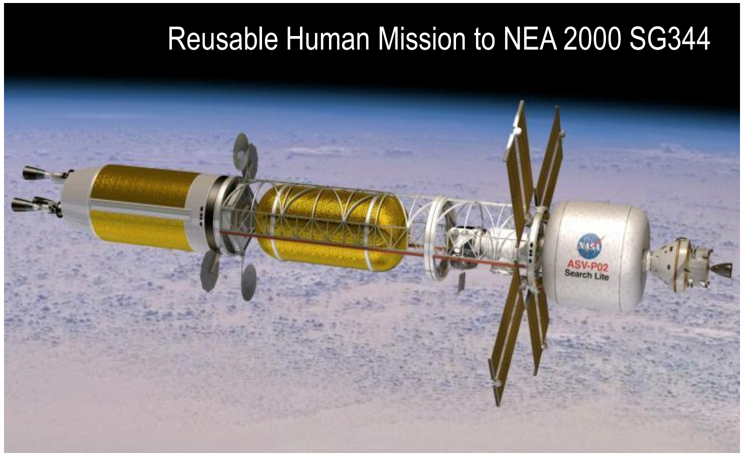
David R. McCurdy (Vantage Partners, LLC at GRC)

at the

20th Advanced Space Propulsion Workshop
Ohio Aerospace Institute

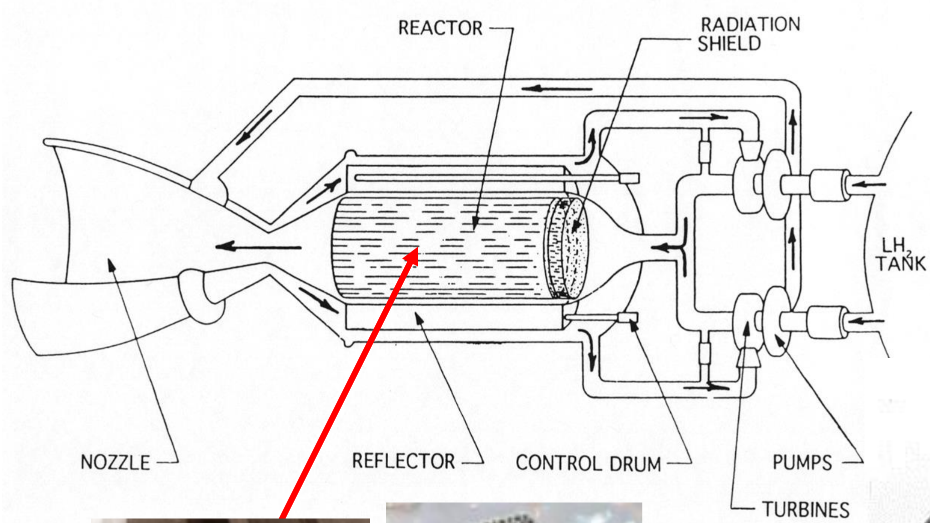


November 17 - 19, 2014

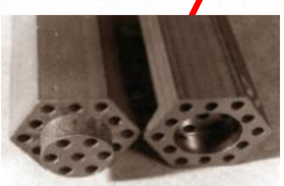
Nuclear Thermal Rocket (NTR) Concept Illustration (Expander Cycle, Dual LH_2 Turbopumps)

"Propelling Us to New Worlds"

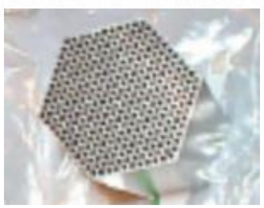
NTR: High thrust / high specific impulse (2 x LOX/LH_2 chemical) engine uses high power density fission reactor with enriched uranium fuel as thermal power source. Reactor heat is removed using H_2 propellant which is then exhausted to produce thrust. Conventional chemical engine LH_2 tanks, turbopumps, regenerative nozzles and radiation-cooled shirt extensions used -- ***"NTR is next evolutionary step in high performance liquid rocket engines"***



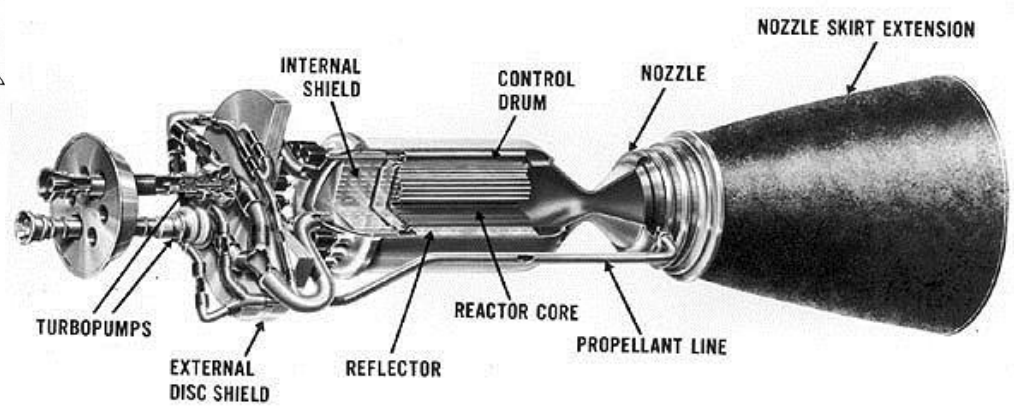
During his famous Moon-landing speech in May 1961, President John F. Kennedy also called for accelerated development of the NTR saying this technology "gives promise of some day providing a means of even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself."



NERVA-derived Composite Fuel



Ceramic Metal (Cermet) Fuel



NTP uses high temperature fuel, produces ~560 MWt (for ~25 klb_f engine) but operates for ≤ 80 minutes on a round trip mission to Mars (DRA 5.0)

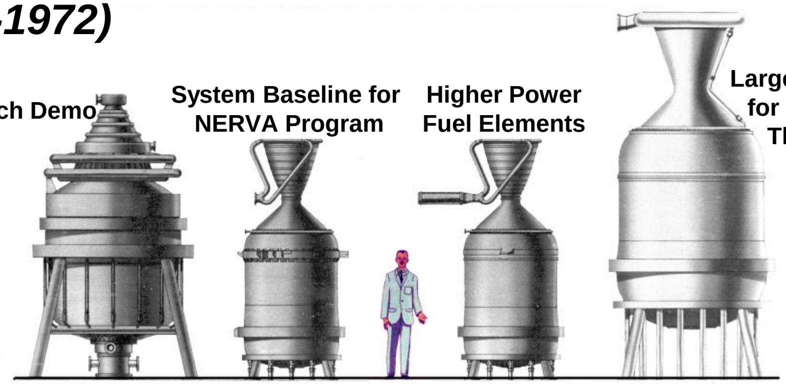
Rover / NERVA Program Summary*

(1959-1972)

The smallest engine tested, the 25 klb_f "Pewee" engine, is sufficient for human Mars missions when used in a clustered arrangement of 3 – 4 engines

- **20 NTR / reactors designed, built and tested at the Nevada Test Site – "All the requirements for a human mission to Mars were demonstrated"**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb_f
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb_f Pewee)
- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb_f NRX-A6 - single burn)
  - ~ 2 hrs (50 klb_f NRX-XE: 27 restarts / accumulated burn time)

**** NERVA: Nuclear Engine for Rocket Vehicle Applications***



The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

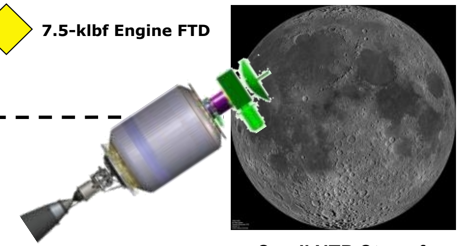
"Propelling Us to New Worlds"

Fiscal Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

Key Milestones

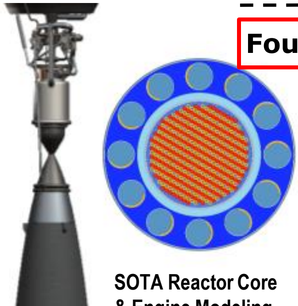
- Fuels Selection
- ATP
- Start / End — GTD Engine Tests
- 7.5-klbf Engine FTD

Notional



Small NTP Stage for Lunar Flyby Mission

Foundational Technology Development



SOTA Reactor Core & Engine Modeling

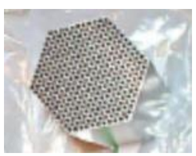
System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis

- In-House & Contractor System Concept Definition, Design, and Analysis
- Reference Concept & Initial Requirements
- Initial GTD Design
- Initial FTD Design
- Initial 25-klbf GTD / FTD Designs

NTP Technology Development and Demonstrations

- Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development
- Primary / Secondary Fuels Selection
- Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests
- Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

NERVA "Composite" Fuel



"Cermet" Fuel

NTP Test Facilities Development

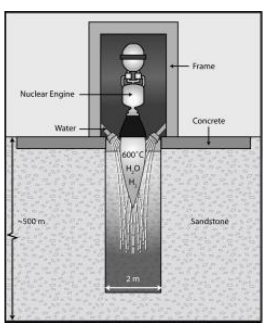
"Fuel-Rich" Engine

- Borehole Demo Testing
- GTF Plan'g/Prel Des

Potential Demos / Mars Flights	
2029-30	Lunar/EM-L2 Flights
2031-33	Mars Cargo Flights
2033-35	Mars Crewed Flights

Fuel Element Irradiation Testing in ATR at INL

Ground & Flight Technology Demonstrators



Affordable SAFE Ground Testing at the Nevada Test Site (NTS)

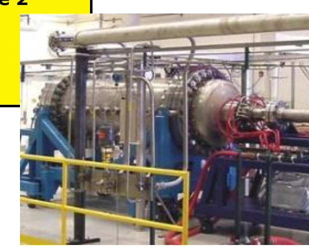
Ground Test Facility (GTF)

- Prel. & Final Design → Construction & Asset Installation → Check-out

Test Articles for Ground & Flight

- CDR GTA
- CDR FTA
- Detailed Design → Fabrication & Subsys. Assembly → Subsys. Test / Engine Assem. → GTA1 → GTA2
- Detailed Design → Fabrication & Subsys. Assembly → Subsys. Test / Engine Assem. → FTA

GTD	Ground Tech Demo
GTA1	Ground Test Article 1
GTA2	Ground Test Article 2
FTA	Flight Test Article
FTD	Flight Tech Demo



NTR Element Environmental Simulator (NTREES)

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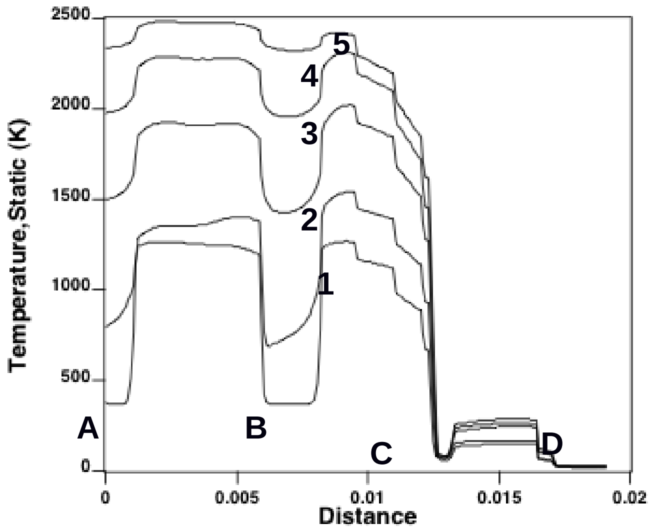
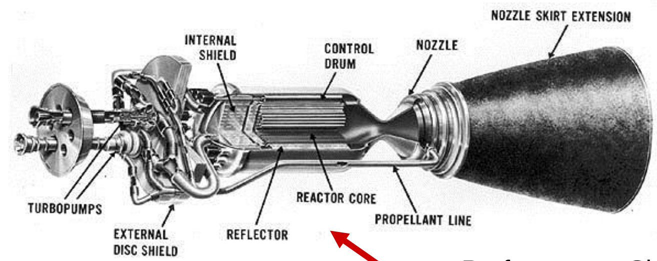
GRC / ORNL Integrated Neutronics, Multi-Physics & Engine Modeling Approach

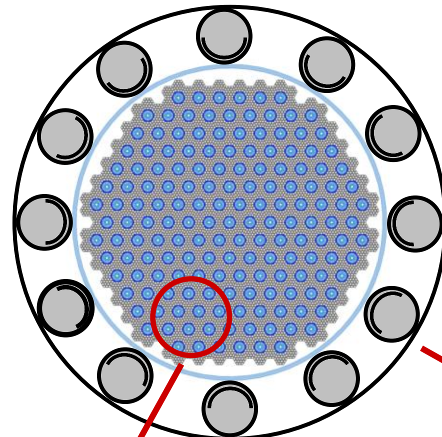
Temperature Distribution Across FE and TT



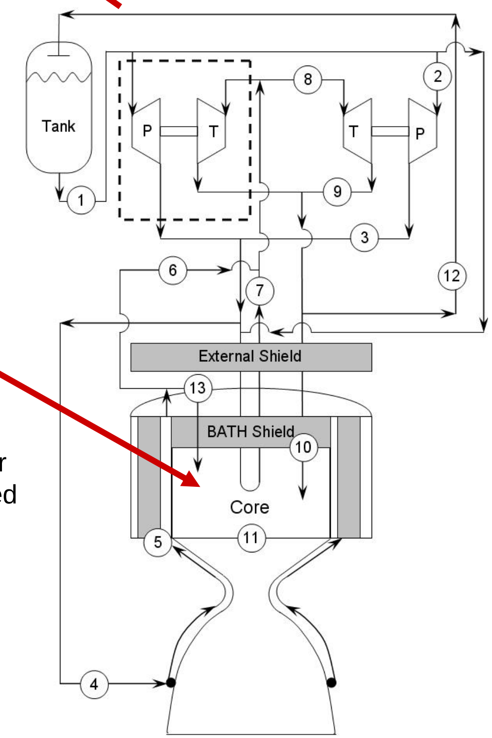
Temperature Distributions at Five Axial Stations
(Numbers Indicate Cold to Hot End Stations)



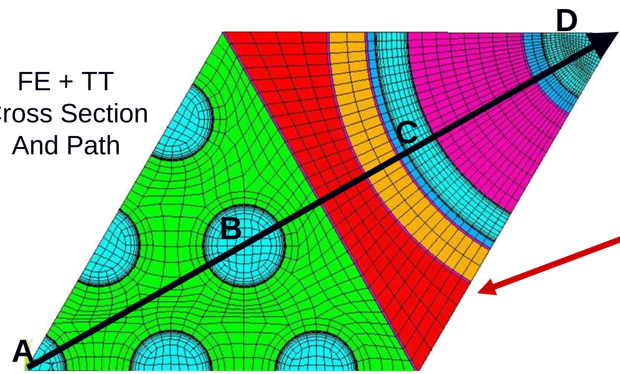
Performance, Size & Mass estimation



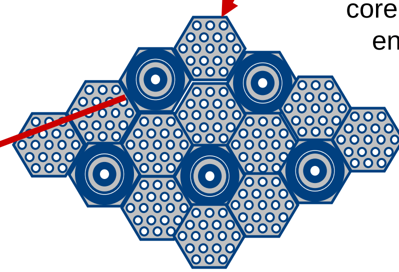
MCNP neutronics for core criticality, detailed energy deposition, and control worth



FE + TT Cross Section And Path



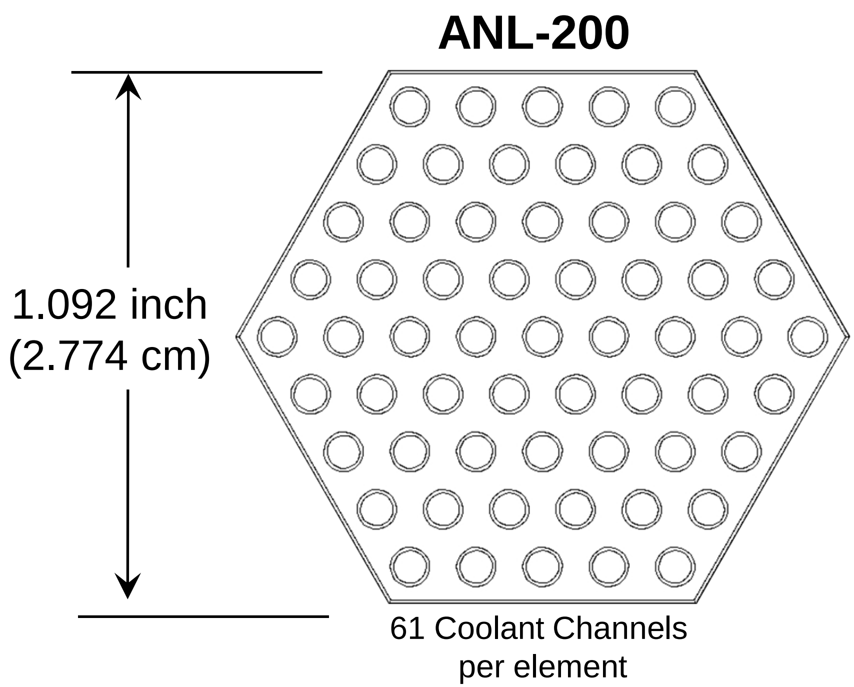
ANSYS Model

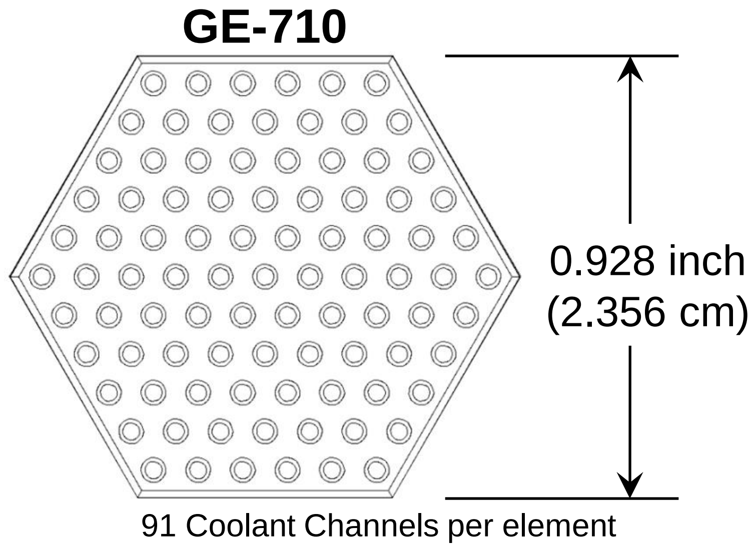


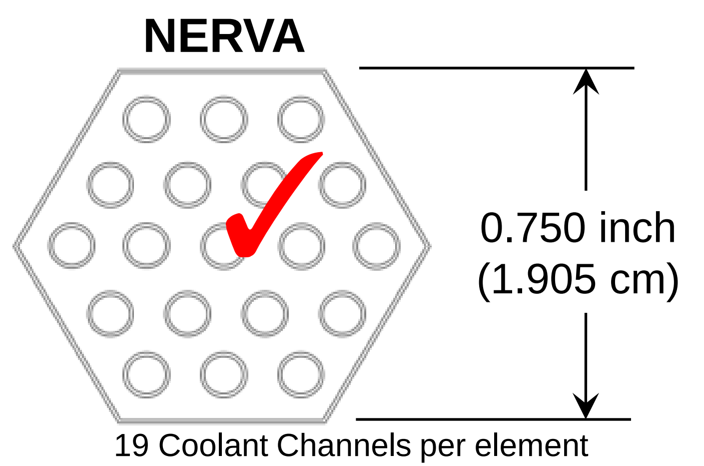
Fuel Element-to-Tie Tube ratio varies with engine thrust level

Nuclear Engine System Simulation (NESS) code has been upgraded to use MCNP-generated data

"Heritage" Fuel Element Size Comparisons (Shown to Relative Scale)





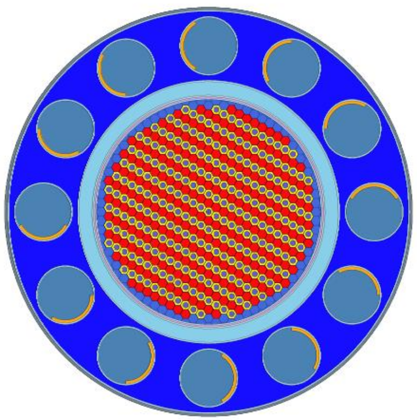


S. K. Borowski et al., "Point of Departure" Designs for Small & Full Size (25 klb_f) Composite & Cermet Fuel NTR Engines (March 20, 2013)

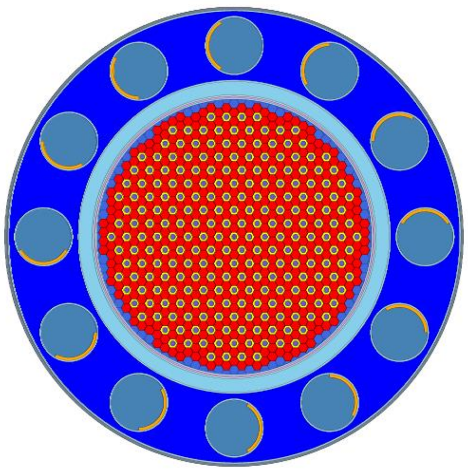
Development of a Common Scalable Fuel Element for Ground Testing and Flight Validation

- During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)

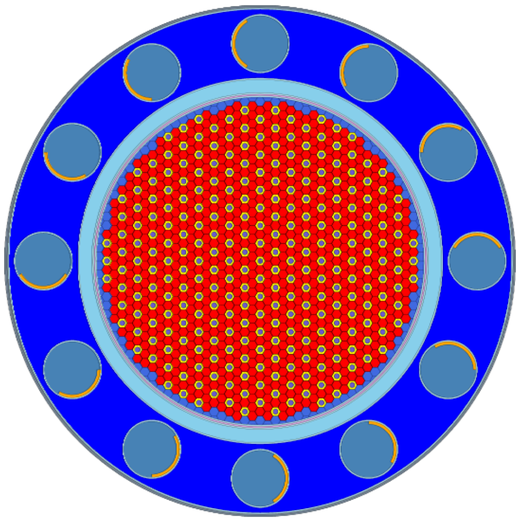
- NASA and DOE are using this same approach: design, build, ground then flight test a small engine using a common fuel element that is scalable to a larger 25 klbf thrust engine needed for human missions



7.5-klb$_f$ low thrust engine



16.4-klb$_f$ SNRE



25-klb$_f$ "Pewee-class" engine
(Radial growth option / sparse pattern)

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846 paper presented at the 47th Joint Propulsion Conference, San Diego, CA

Fuel Element (FE) – Tie Tube (TT) Arrangements for NERVA-derived NTR Engines

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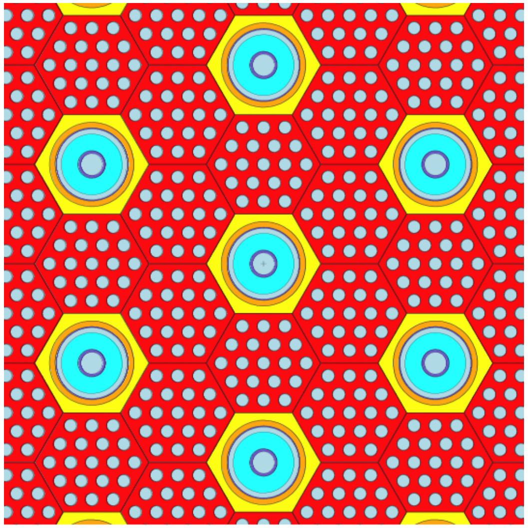
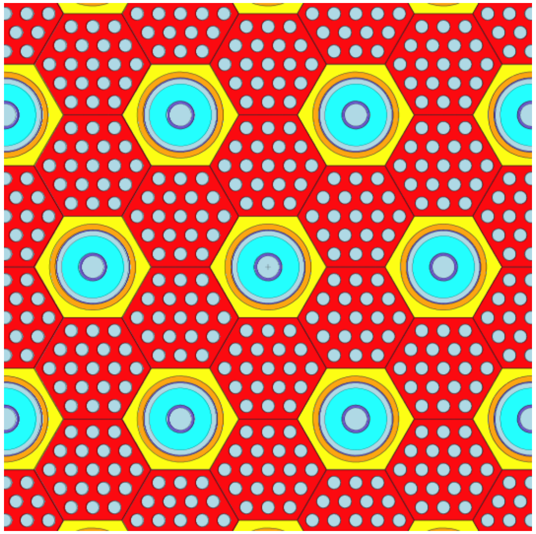
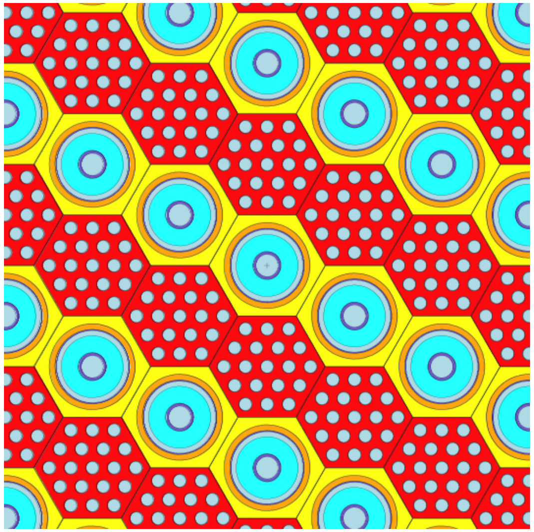
"Sparse" FE – TT Pattern used for Large Engines	"SNRE" FE – TT Pattern used in Small Nuclear Rocket Engine	"Dense" FE – Tie Tube Pattern used in Lower Thrust Engines
		
Each FE has 4 adjacent FEs and 2 adjacent TTs with a FE to TT ratio of ~3 to 1	Each FE has 3 adjacent FEs and 3 adjacent TTs with a FE to TT ratio of ~2 to 1	Each FE has 2 adjacent FEs and 4 adjacent TTs with a FE to TT ratio of ~1 to 1

NOTE: An important feature common to both the Sparse and SNRE FE – TT patterns is that each tie tube is surrounded by and provides mechanical support for 6 fuel elements

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

Performance Characteristics for Small & Full Size NERVA-derived Engine Designs – Composite Fuel

Performance Characteristic	7,420-lbf Option	SNRE Baseline	Axial Growth Option Nominal	Axial Growth Option Enhanced	Radial Growth Option Nominal	Radial Growth Option Enhanced
Engine System						
Thrust (klb_f)	7.42	16.4	25.1	25.1	25.1	25.1
Chamber Inlet Temperature (K)	2736	2695	2790	2940	2731	2807
Chamber Pressure (psia)	1000	450	1000	1000	1000	1000
Nozzle Expansion Ratio (NAR)	300:1	100:1	300:1	300:1	300:1	300:1
Specific Impulse (s)	894	875	906	941	894	913
Engine Thrust-to-Weight	1.87	2.92	3.50	3.50	3.60	3.60
Reactor						
Active Fuel Length (cm)	89.0	89.0	132.0	132.0	89.0	89.0
Effective Core Radius (cm)	14.7	29.5	29.5	29.5	35.2	35.2
Engine Radius (cm)	43.9	49.3	49.3	49.3	55.0	55.0
Element Fuel/Tie Tube Pattern Type	Dense	SNRE	SNRE	SNRE	Sparse	Sparse
Number of Fuel Elements	260	564	564	564	864	864
Number of Tie Tube Elements	251	241	241	241	283	283
Fuel Fissile Loading (g U per cm^3)	0.60	0.60	0.25	0.25	0.45	0.45
Maximum Enrichment (wt% U-235)	93	93	93	93	93	93
Maximum Fuel Temperature (K)	2860	2860	2860	3010	2860	2930
Margin to Fuel Melt (K)	40	40	190	40	110	40
U-235 Mass (kg)	27.5	59.6	36.8	36.8	68.5	68.5

NOTE: Fuel Matrix Power Density: 3.437 MW_t / liter

SOTA "Pewee-class" Engine Parameters

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846

Small 7.5 klb$_f$ NTP Engine and Stage for 2025 Lunar Flyby FTD Mission

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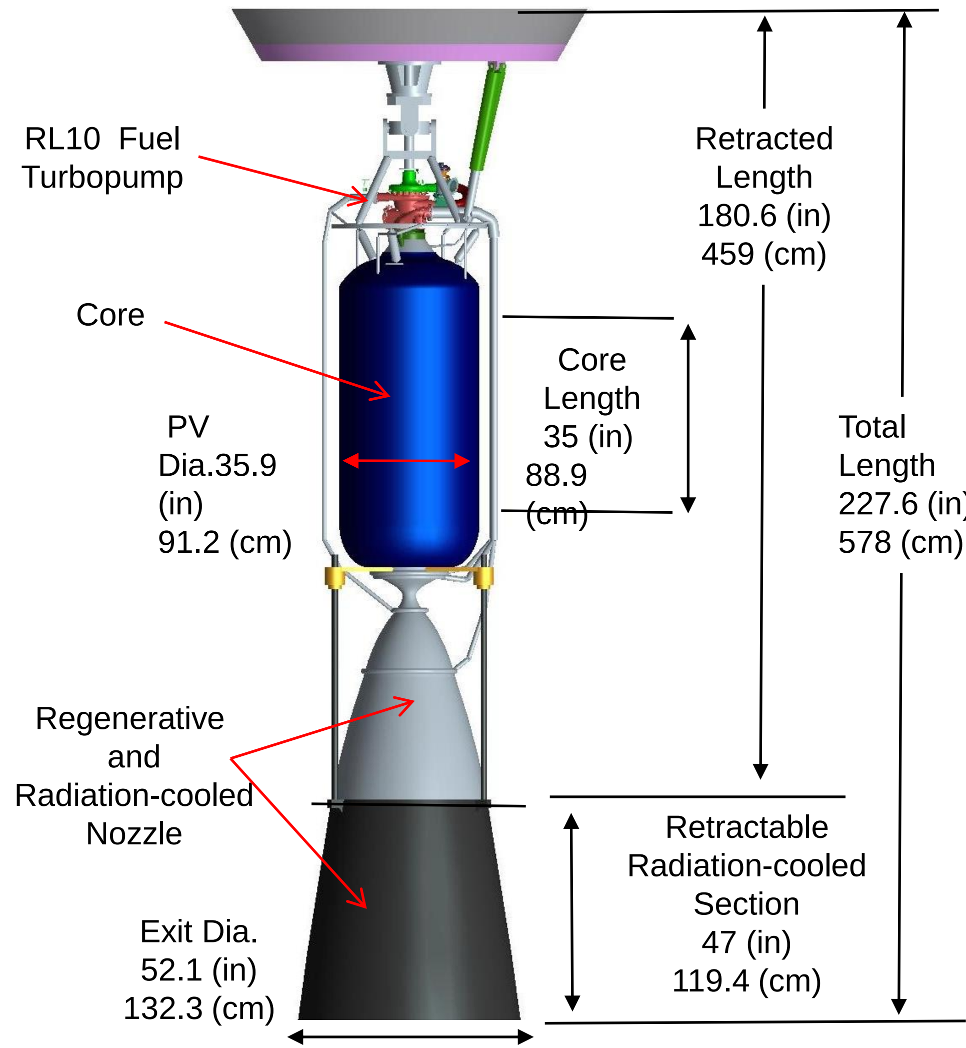
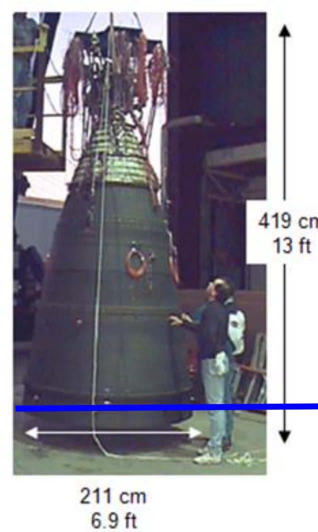
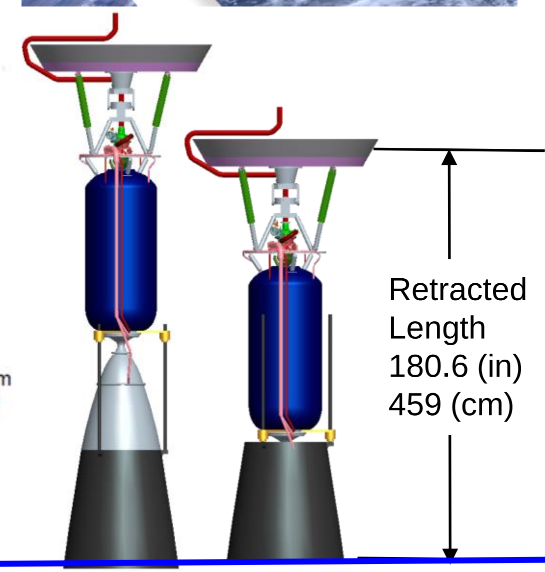
AEROJET ROCKETDYNE

- IMLEO ~12.72 t
- F ~7.5 klb$_f$, I$_{sp}$ ~900s,
- LH$_2$ mass ~5.07 t
- Stage dry mass ~7.40 t
- Burn time ~20.9 mins

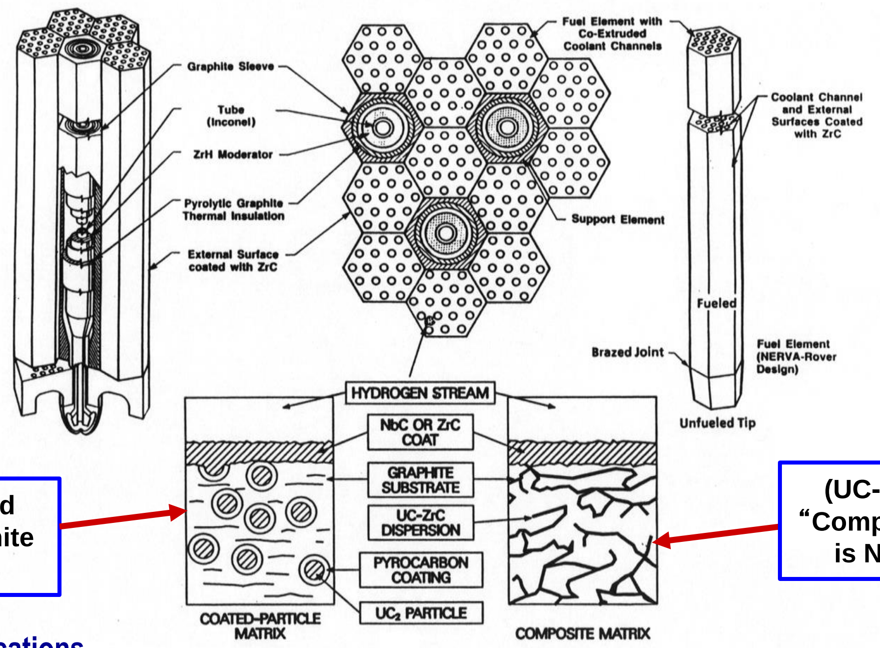


LO2/LH2 RL10B-2 Tvac 24,750-lbf





"Heritage" Coated Particle & Composite SNRE FE / TT Arrangement and Engine Performance Parameters



Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

(UC-ZrC) in Graphite "Composite" Matrix Fuel is NERVA Baseline

Table 2 - For Lunar Mission Applications

Baseline Small Nuclear Rocket Engine (SNRE) Performance Parameters:

- Engine Cycle: Expander
- Thrust Level: 16.675 klb_f
- Hydrogen Exhaust Temperature: 2726 K
- Chamber Pressure: 450 psia
- Nozzle Area Ratio: 300:1
- Specific Impulse (I_{sp}): ~900 s
- Hydrogen Flow Rate: ~8.4 kg/s
- F / W_{eng} Ratio: ~3.06
- Engine Length: ~6.1 m
- Nozzle Exit Diameter: ~2.31 m
- FE Length ~0.89 m (~35 inches)
- No. FEs / TTs: 564 / 241
- FE-to-TT Ratio: ~2:1
- Reactor Power Level: ~367 MWt
- Fuel Matrix Power Density: ~3.44 MWt / liter
- U-235 Enrichment: 93%
- Fuel Loading: ~0.6 grams / cm^3
- U-235 Inventory: ~60 kg

(Ref: S.K. Borowski, et al., AIAA-2013-5465)

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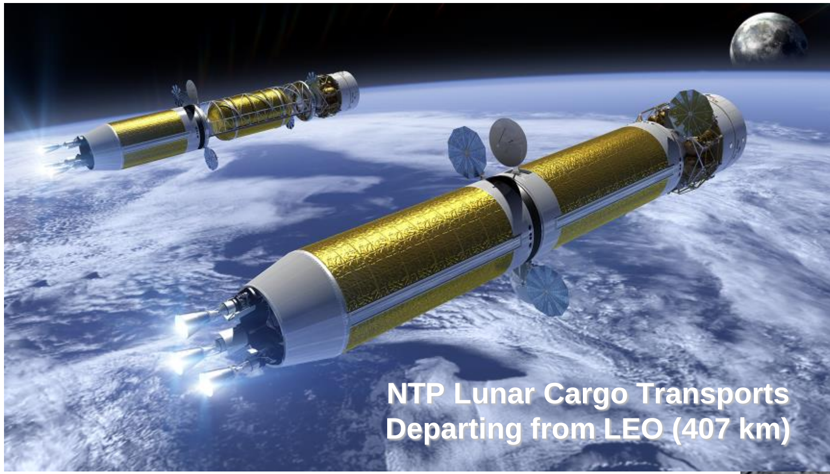
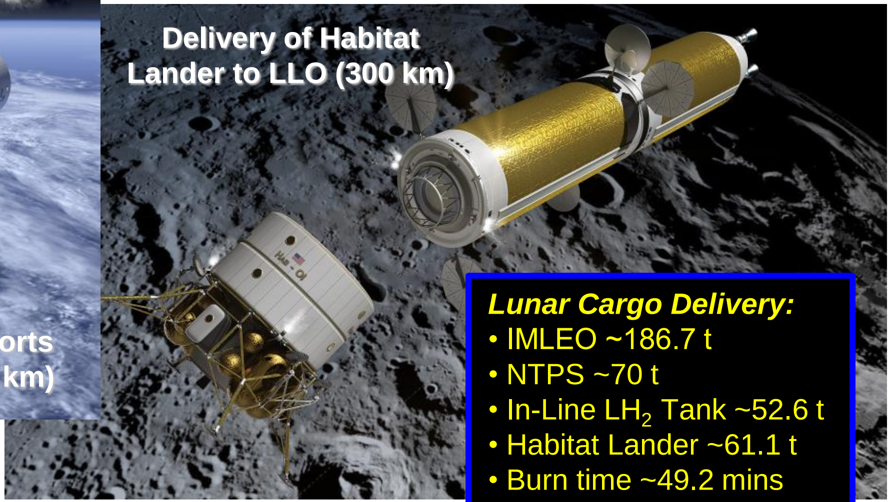
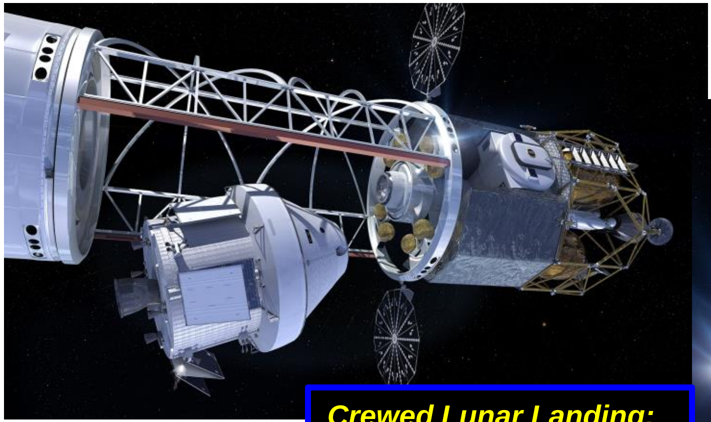
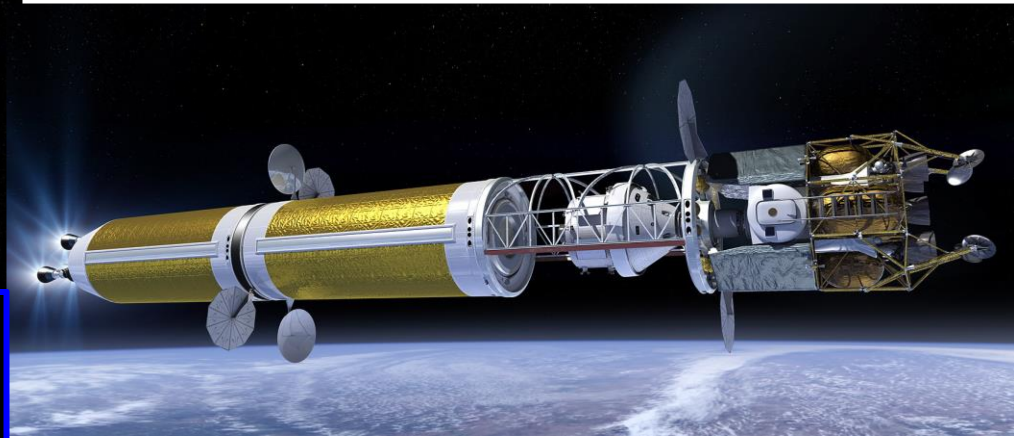
The NTPS with In-Line LH_2 Tank Allows Reusable Cargo Delivery and Crewed Missions to the Moon





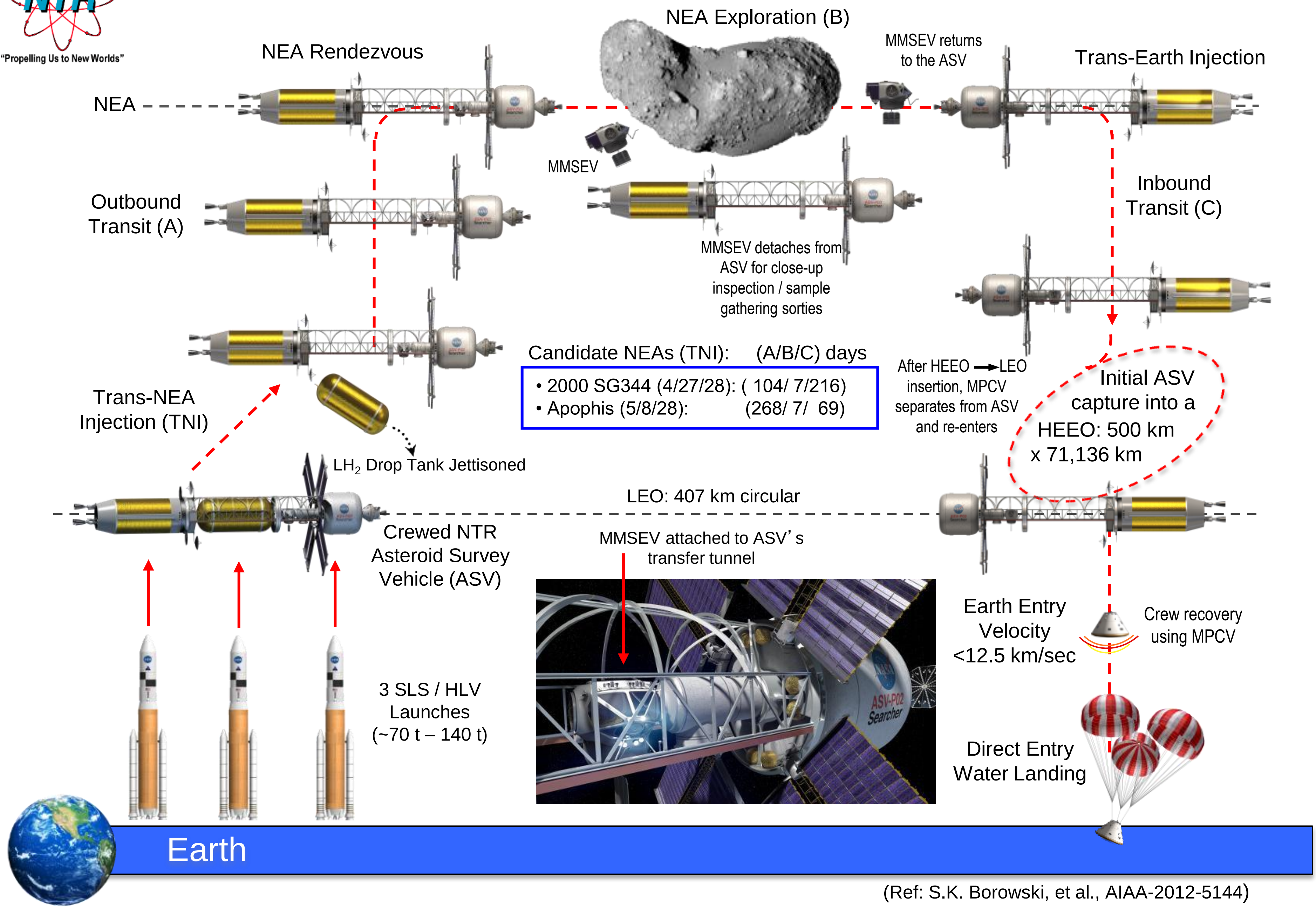
Lunar Cargo Delivery:
- IMLEO ~186.7 t
- NTPS ~70 t
- In-Line LH_2 Tank ~52.6 t
- Habitat Lander ~61.1 t
- Burn time ~49.2 mins





Crewed Lunar Landing:
- IMLEO ~188.6 t
- NTPS ~70 t
- LDAV and PL ~34.5 t
- MPCV, 4-Crew ~14.4 t
- Burn time ~55 mins

Crewed NTR NEA Survey Mission – Reusable Mode



(Ref: S.K. Borowski, et al., AIAA-2012-5144)

"Searcher" and "Search Lite" ASV Options for Reuable and Expendable Missions to "Apophis" in 2028

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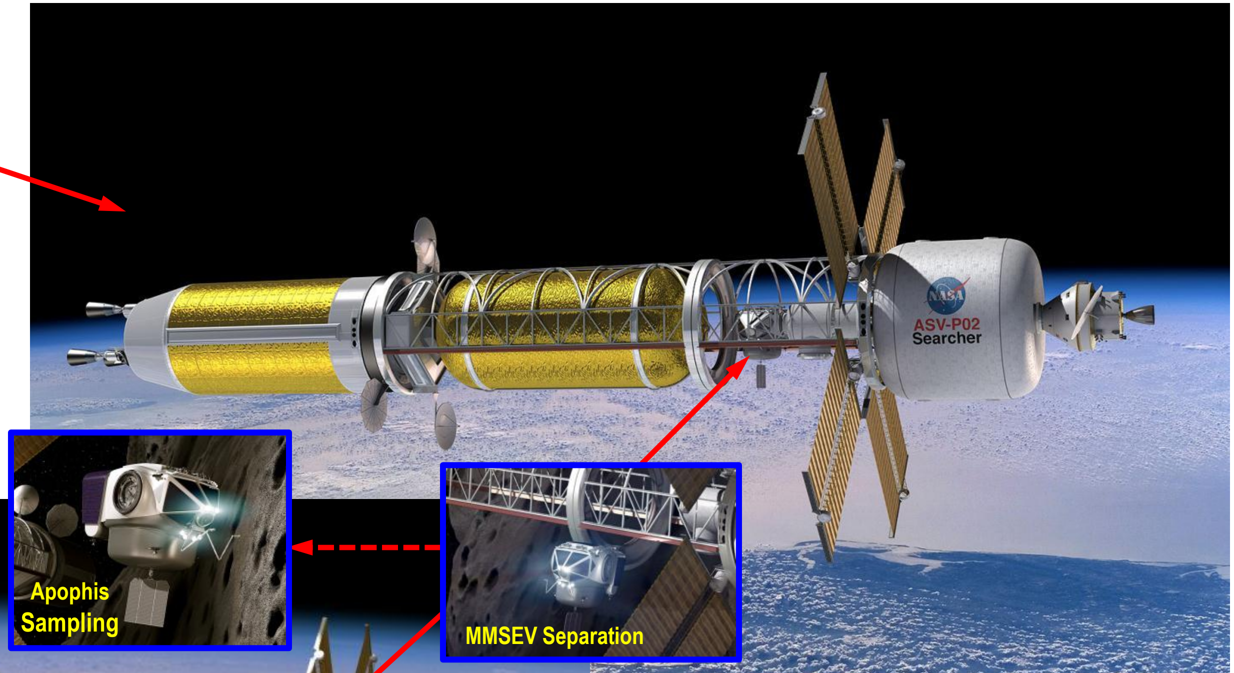
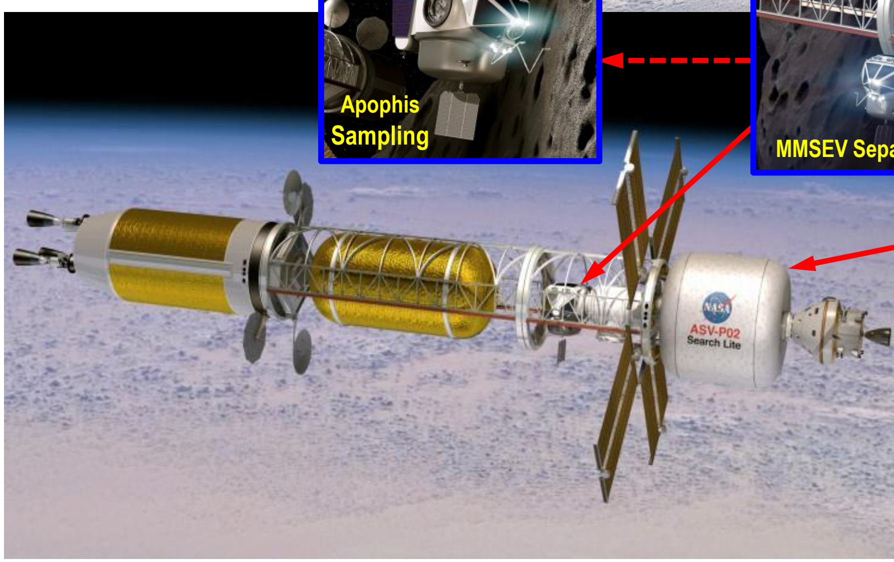
(Ref: S.K. Borowski, et al., AIAA-2012-5144)

Reusable Apophis Mission
(LEO – NEA – 24-hr EEO)
- 6 Crew
- 3 – 25 klb_f NTRs
- 10 m dia. LH_2 tanks
- PL + MPCV ~62.3 t
- IMLEO ~326.2 t
- Max Lift ~138.1 t (NTPS)
- Total Mission Burn Time: 77.3 min





Expendable Apophis Mission
(LEO – NEA – Direct Entry)
- 4 crew
- 3 – 25 klb_f NTRs
- 8.4 m dia. LH_2 tanks
- PL + MPCV ~56.3 t
- IMLEO ~222.6 t
- Max Lift ~93.0 t (NTPS)
- Total Mission Burn Time: 43.8 min

Reusable NTP Vehicles for NEA, Lunar Cargo and Crewed Landing Missions with Max Lift to LEO ~70 t

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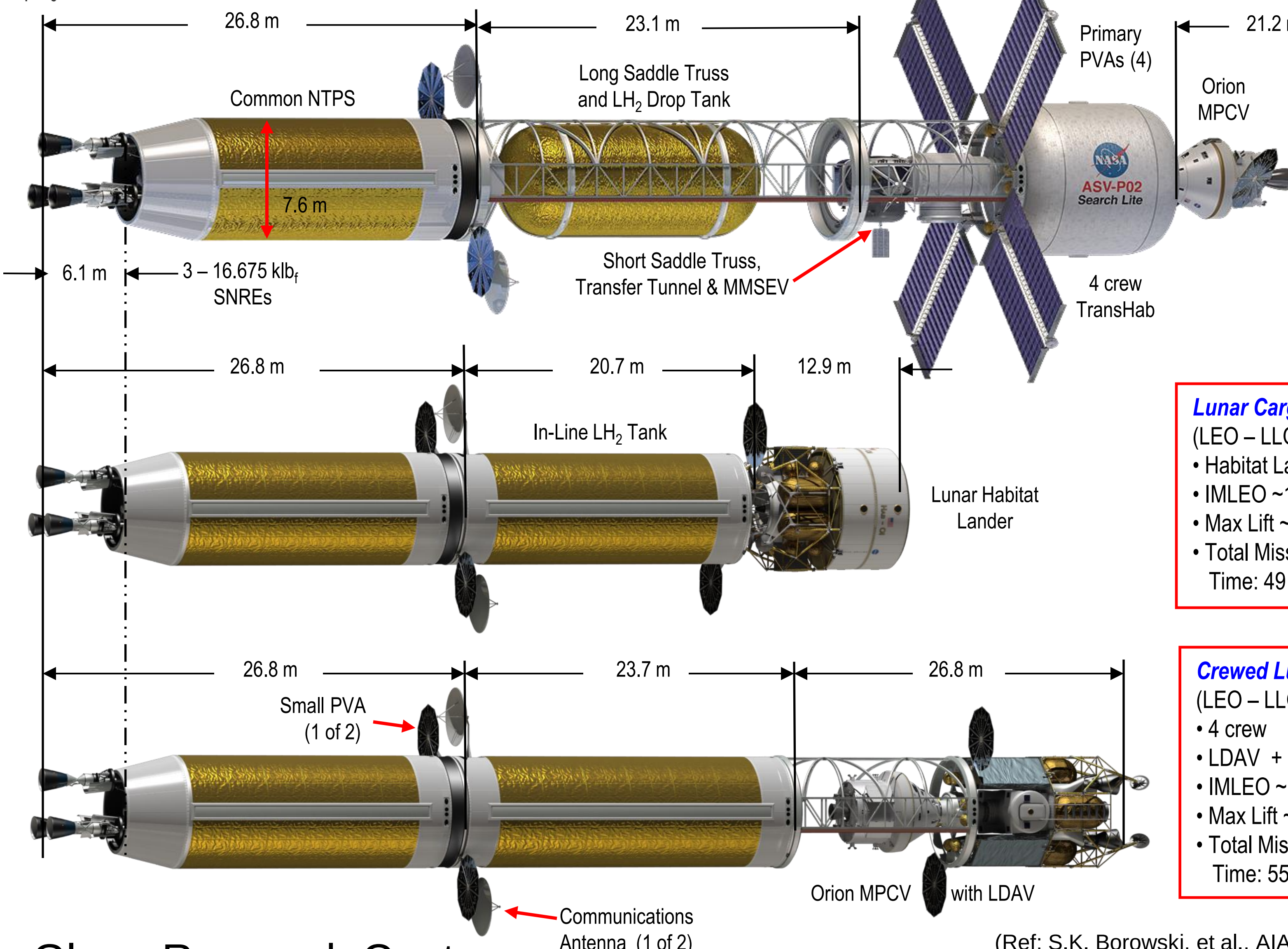


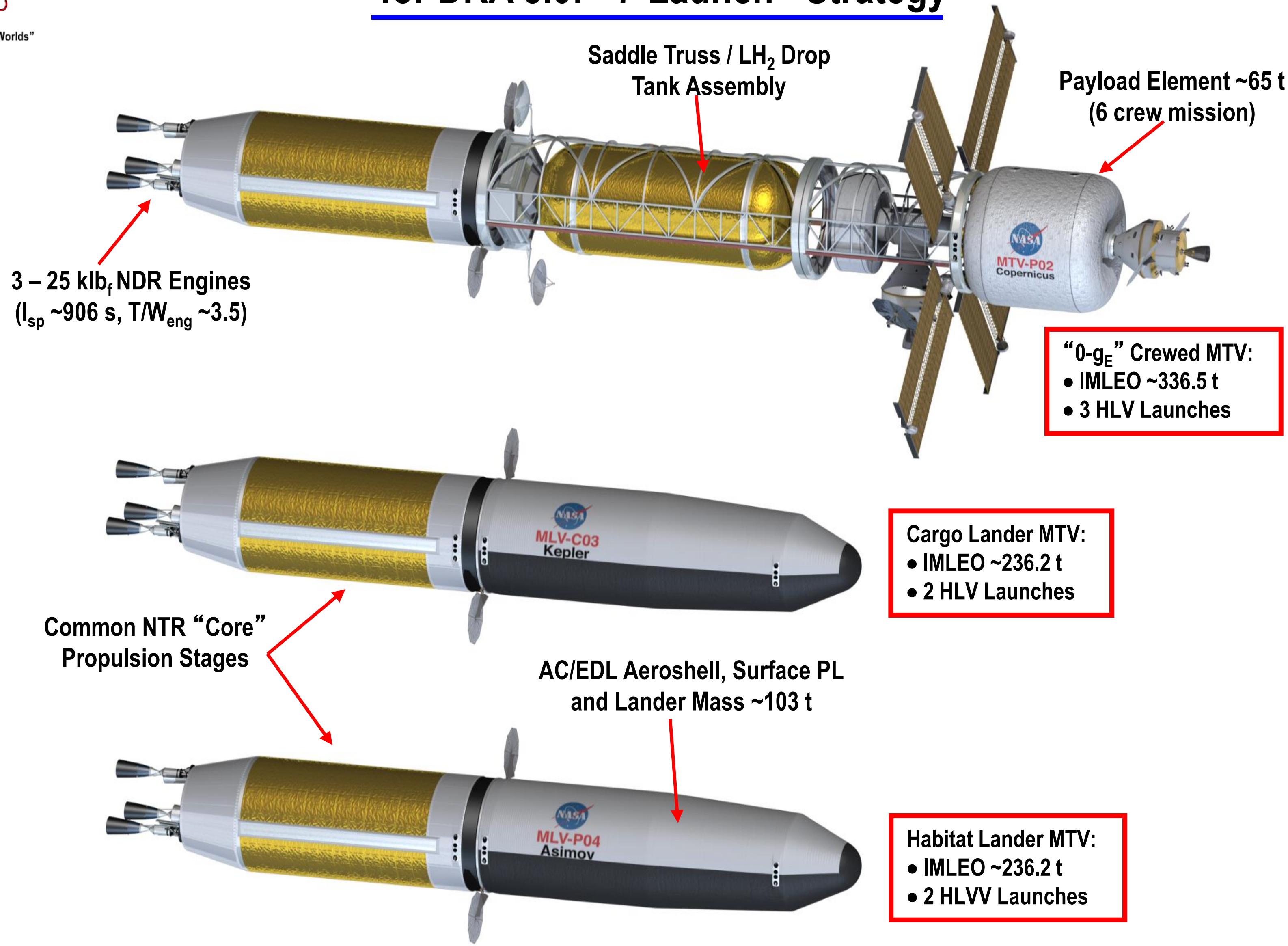
ASV: 2000 SG344 (2028)
(LEO – NEA – 6-hr EEO)
- 4 crew
- PL + MPCV ~55.3 t
- IMLEO ~179.6 t
- Max Lift ~69.5 t (NTPS)
- Total Mission Burn Time: 54.5 min

Lunar Cargo Delivery:
(LEO – LLO – 24-hr EEO)
- Habitat Lander ~61.1 t
- IMLEO ~186.7 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: 49.2 min

Crewed Lunar Landing:
(LEO – LLO – 24-hr EEO)
- 4 crew
- LDAV + MPCV ~48.9 t
- IMLEO ~188.6 t
- Max Lift ~70 t (NTPS)
- Total Mission Burn Time: 55 min

(Ref: S.K. Borowski, et al., AIAA-2013-5465)

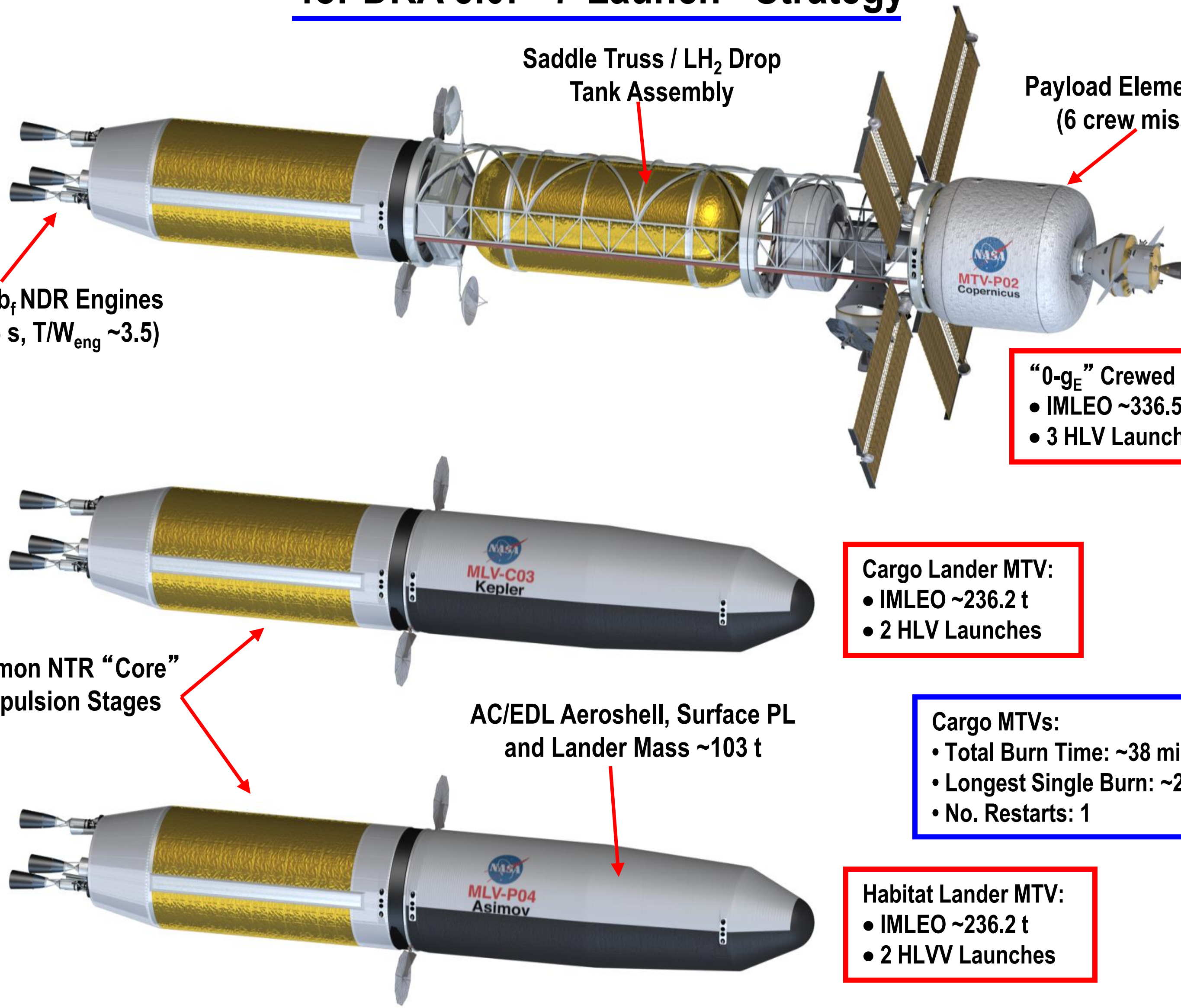
NTR Crewed & Cargo Mars Transfer Vehicles (MTVs) for DRA 5.0: "7-Launch" Strategy



(Ref: S.K. Borowski, et al., AIAA-2009-5308)

NTR Crewed & Cargo Mars Transfer Vehicles (MTVs) for DRA 5.0: "7-Launch" Strategy

"Propelling Us to New Worlds"



"0-g_E" Crewed MTV:
- IMLEO ~336.5 t
- 3 HLV Launches

Cargo Lander MTV:
- IMLEO ~236.2 t
- 2 HLV Launches

Cargo MTVs:
- Total Burn Time: ~38 min
- Longest Single Burn: ~22 min
- No. Restarts: 1

Habitat Lander MTV:
- IMLEO ~236.2 t
- 2 HLVV Launches

(Ref: S.K. Borowski, et al., AIAA-2009-5308)

"Copernicus" Crewed NTR Mars Transfer Vehicle (MTV) Configuration Options for DRA 5.0

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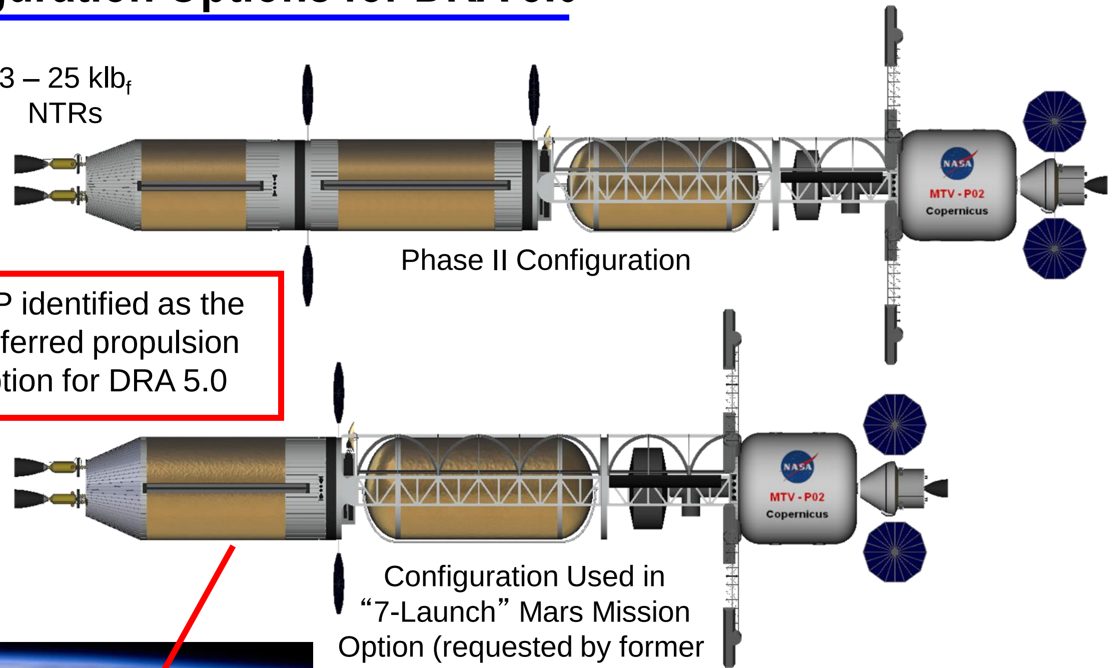
DRA 5.0 Crewed MTV Options:
- "4-Launch" in-line configuration
- Ares-V: 110 t; 9.1 m OD x 26.6 m L
- IMLEO: ~356.5 t (6 crew)
- Total Mission Burn Time: ~84.5 min
- Largest Single Burn: ~30.7 min
- No. Restarts: 3

- "3-Launch" in-line configuration
- Ares-V: 140 t; 10 m OD x 30 m L
- IMLEO: 336.5 t (6 crew)
- Total Mission Burn Time: ~79.2 min
- Largest Single Burn: ~44.6 min
- No. Restarts: 3

NTP identified as the preferred propulsion option for DRA 5.0



Copernicus was sized to perform all fast conjunction missions in 2033 -2045 period

United States' National Space Policy (June 28, 2010, pg. 11) specifies that NASA shall: By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars & return them safely to Earth.

(Refs: Mars DRA 5.0 Study, NASA-SP-2009-566; Borowski et al., AIAA-2009-5308)

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Potential Evolution of Composite Fuel NTRE Size and Performance Levels Supporting the HAT “Evolvable Mars Campaign”

Requirements / Missions	Engine Thrust (klb$_f$)	T/W$_{eng}$	T$_{ex}$ (°K)	I$_{sp}$ (s)	No. Engines	Fuel Loading (gU/cm^3)	U-235 Mass (kg)	Longest Single burn (min)	Total burn duration (min)	No. burns
Early FTD or Robotic Science	7.4	~1.9	2736	894	1	0.6	27.5	~20.9-22	~20.9-29.5	1-2
Lunar Cargo	16.7	~3.1	2726	900	3	0.6	60	~21.4	~49.2	5
Lunar Crewed	16.7	~3.1	2726	900	3	0.6	60	~20.9	~55	5
NEA - *Apophis* Piloted	25	~3.5	2790 - 2940	906-940	3	0.25	36.8	~25 - 37.2	~43.8 - ~77.3	4-5
Mars Cargo	25	~3.5	2790 - 2940	906-940	3	0.25	36.8	~22	~38	2
Mars Piloted	25	~3.5	2790 - 2940	906–940	3	0.25	36.8	~44.5	~79.2	4

- The criticality-limited 7.4 klb$_f$ engine produces ~161 MW$_t$ of thermal power and has maximum fuel temperature of 2860 K
- The 16.7 klb$_f$ SNRE produces ~367 MW$_t$, and operates at a chamber pressure of ~3.1 MPa (~450 psia) with NAR ~300:1
- The 25 klb$_f$ Pewee-class engine produces ~560 MW$_t$ of thermal power and has maximum fuel temperature of 3010 K
- Other key performance parameters for the criticality-limited, SNRE & Pewee-class engines provided in NETS-2014 paper

The engine design and mission performance parameters developed thus far provide important data to help guide future non-nuclear / nuclear irradiation testing and fuel down selection process

Ref: S. K. Borowski et al., NETS-2014, Feb. 24-26, 2014