Space Technology Mission Directorate

Game Changing Development Program

Nuclear Thermal Propulsion Project – Cryogenic Fluid Management Studies for NTP

Jonathan Stephens, Arthur Werkheiser, Eric Carlberg, Jason Hartwig and David Plachta, NASA, August, 2018

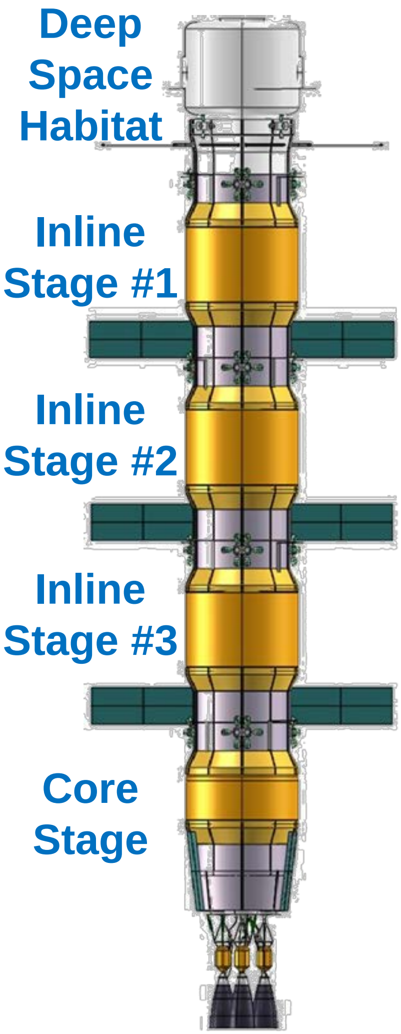
NTP CFM Concept of Operations Key Performance Requirements

Nuclear Thermal Propulsion

OBJECTIVE(S):

- **Develop the NTP CFM Concept of Operations**
  - **Vehicle Description ✓**
  - **Mission Analysis & Design Reference Missions ✓**
  - **Ground Processing and Launch Operations ✓**
  - **Aggregation ✓**
  - **Flight Operations ✓**
  - **Off-Nominal Operations**
    - o **Pre-launch**
    - o **Flight**
  - **System Verification Test at SSC**

- **Identify CFM Requirements to close the mission**
  - **Enabling**
  - **Potentially enhancing**
  - **Define Key Performance Parameters**



NTP Conceptual Design

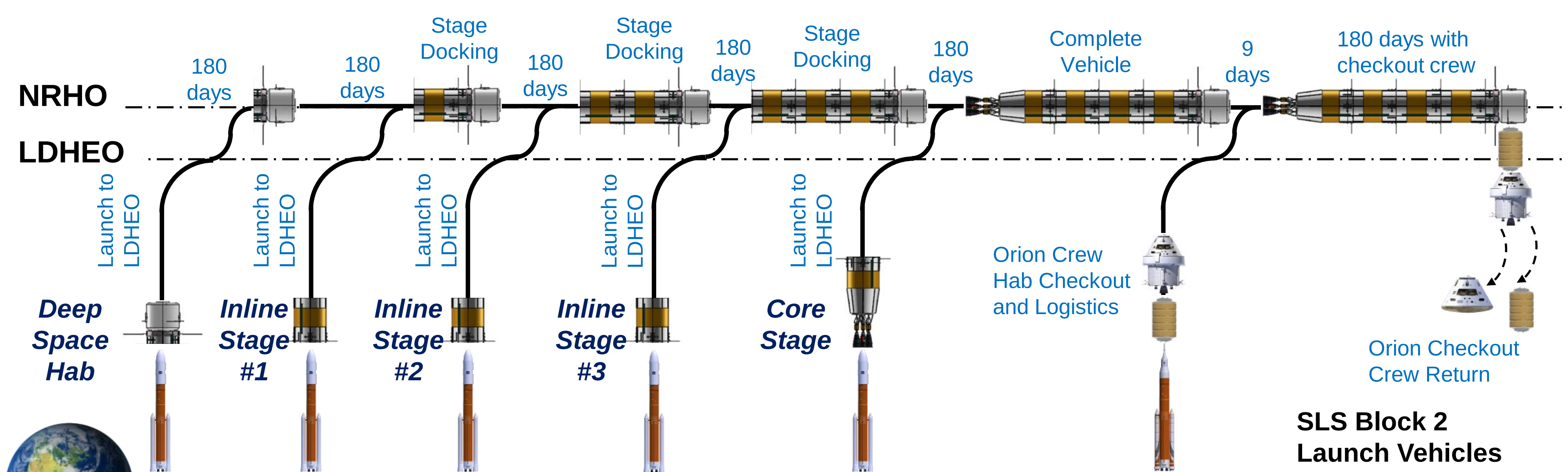
NTP Crew Vehicle Aggregation in NRHO

Nuclear Thermal Propulsion

1 Sol

10 Sol

- Launch elements separately to LDHEO
- 180 day low ΔV transfer to NRHO using RCS
- Aggregate, rendezvous and dock stages in NRHO
- Checkout and ready vehicle

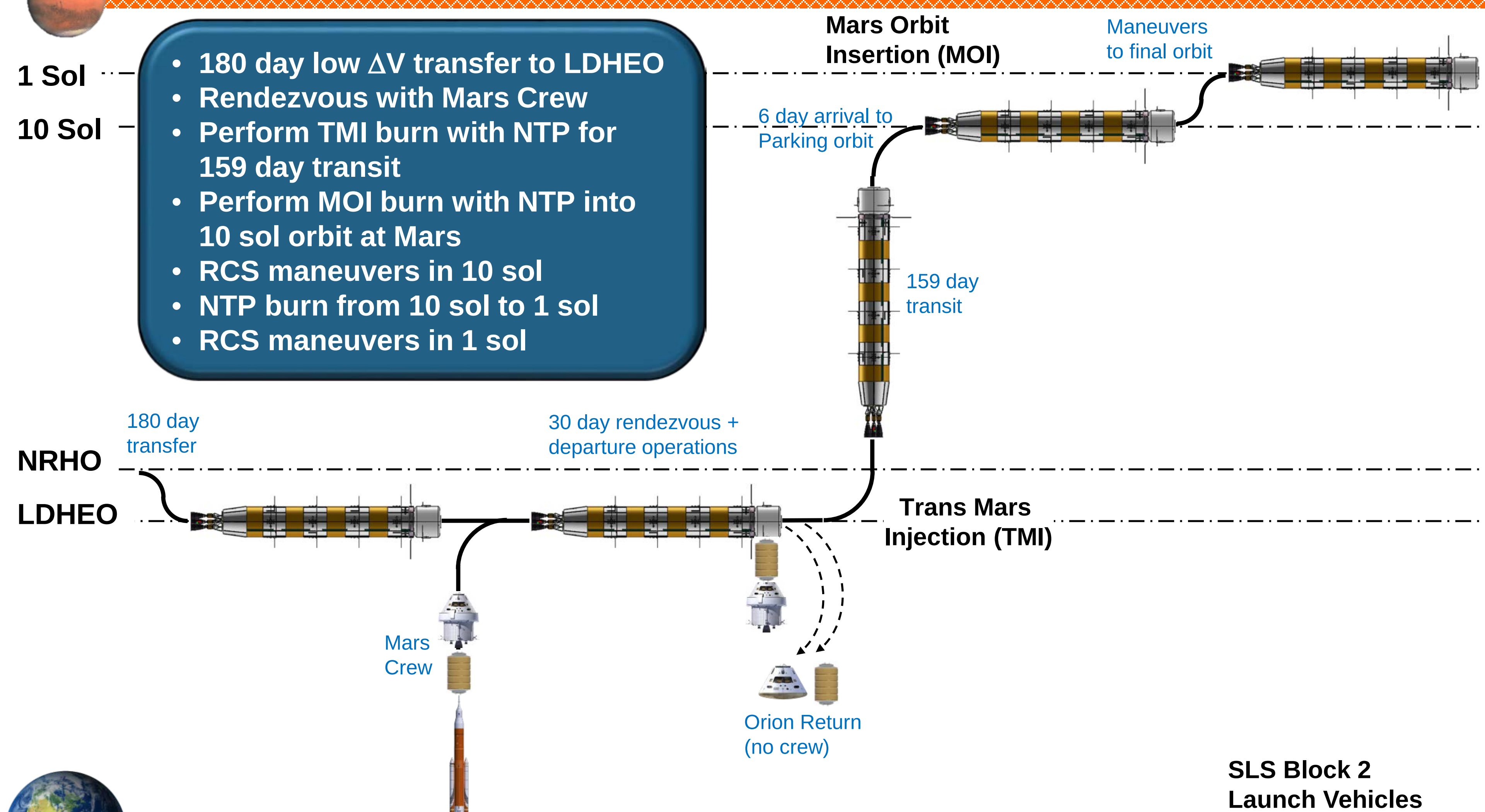


NTP Vehicle Conceptual Design

NTP Crew Vehicle
Earth to Mars Transit

Nuclear Thermal Propulsion

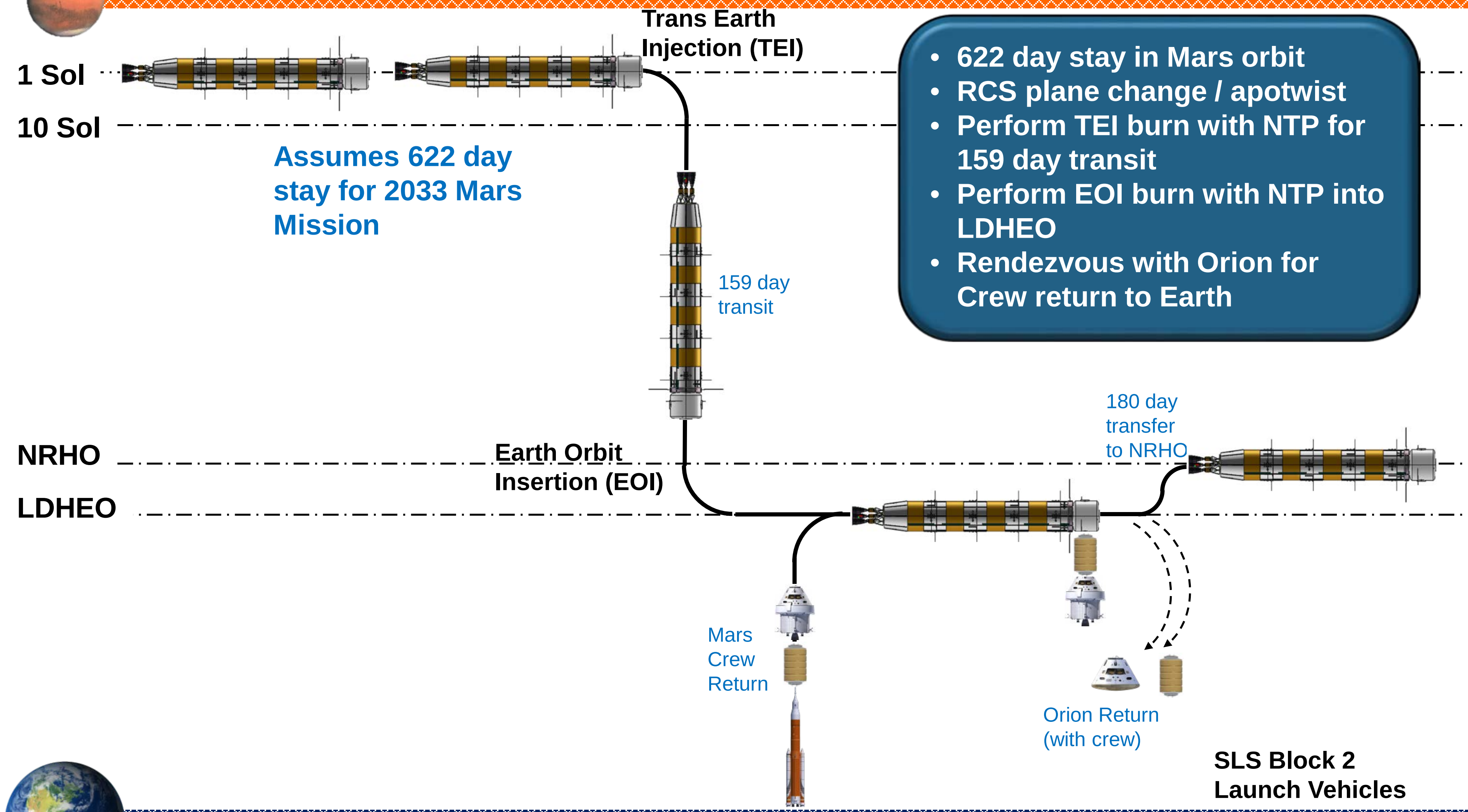
- 180 day low ΔV transfer to LDHEO
- Rendezvous with Mars Crew
- Perform TMI burn with NTP for 159 day transit
- Perform MOI burn with NTP into 10 sol orbit at Mars
- RCS maneuvers in 10 sol
- NTP burn from 10 sol to 1 sol
- RCS maneuvers in 1 sol



NTP Vehicle Conceptual Design

NTP Crew Vehicle Mars to Earth Transit

Nuclear Thermal Propulsion



NTP Vehicle Conceptual Design

Aggregation Timeline

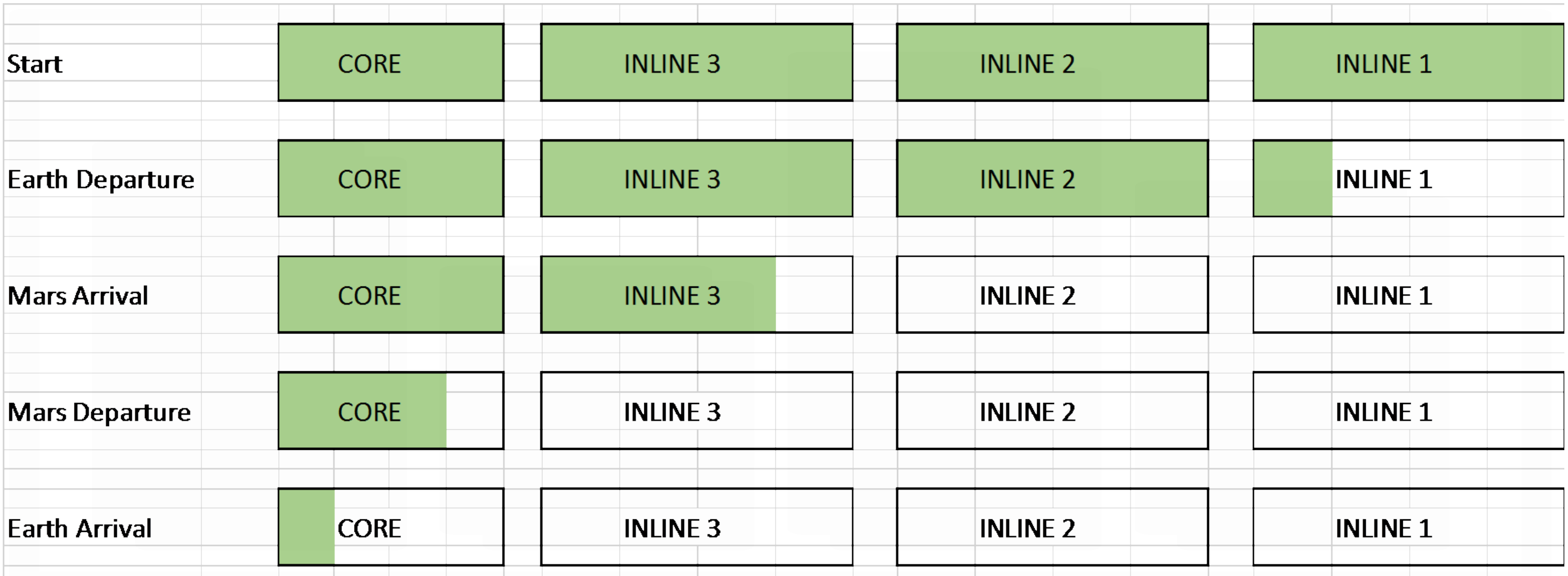
Nuclear Thermal Propulsion

Mission Phase		Launch	Assembly	Assembly	Assembly	Assembly	NRHO	Check Out	LDHEO
MET (days)		0	180	365	545	730	1000	1090	1100
Delta (days)		0	180	185	180	185	270	90	10
Hab		Launch	180	365	545	730	1000	1090	1100
Inline Tank 1			Launch	180	365	545	815	905	915
Inline Tank 2				Launch	180	365	635	725	735
Inline Tank 3					Launch	180	450	540	550
Core						Launch	270	360	370

- SLS Launch cadence allows a launch every ~180 days
- Inline Tank 1 spends 3.0 years in orbit before Trans Mars Injection
- Each element is fully capable of maneuvering: RCS, Guidance
- Each element will dock with the “stack” as soon as possible
- NRHO & LDHEO have similar thermal environments and are the “warmest” orbits of all mission phases.
  - Thermally, both orbits are a factor of 3 to 4 lower than LEO
- This Mission Design is Notional

Hydrogen Consumption - Notional

Nuclear Thermal Propulsion



- **Based on baselined Hydrogen use – Cascade flow**
- **This is likely NOT the best way to managed the Hydrogen**
  - **Core tank bottom gets Gamma Ray & Neutron heating**
- **<u>This analysis assumes Passive CFM is optimized, Active Cooling (Cryocoolers) are utilized and Low Leakage, Long Duration Cryocouplers and Valves are utilized to achieve “near zero” losses.</u>**
- **Each of the 3 engines require 28 pounds/sec of Hydrogen**

Manned Mars Mission Timeline

Nuclear Thermal Propulsion

Mission Phase		Trans Mars	Mars Orbit	Mars Loiter	Depart Prep	Earth Trans	Earth Orbit	Orion
MET (days)		1265	1271	1881	1891	2056	2063	2064
Delta (days)		165	6	610	10	165	7	1
Manned (days)		0	165	171	781	791	956	963
Hab		1265	1271	1442	2223	3014	3970	4933
Inline Tank 1		1080	1086	Empty	Empty	Empty	Empty	Empty
Inline Tank 2		900	906	1516	1526	Empty	Empty	Empty
Inline Tank 3		715	721	1331	1341	1506	1513	1514
Core		535	541	1151	1161	1326	1333	1334

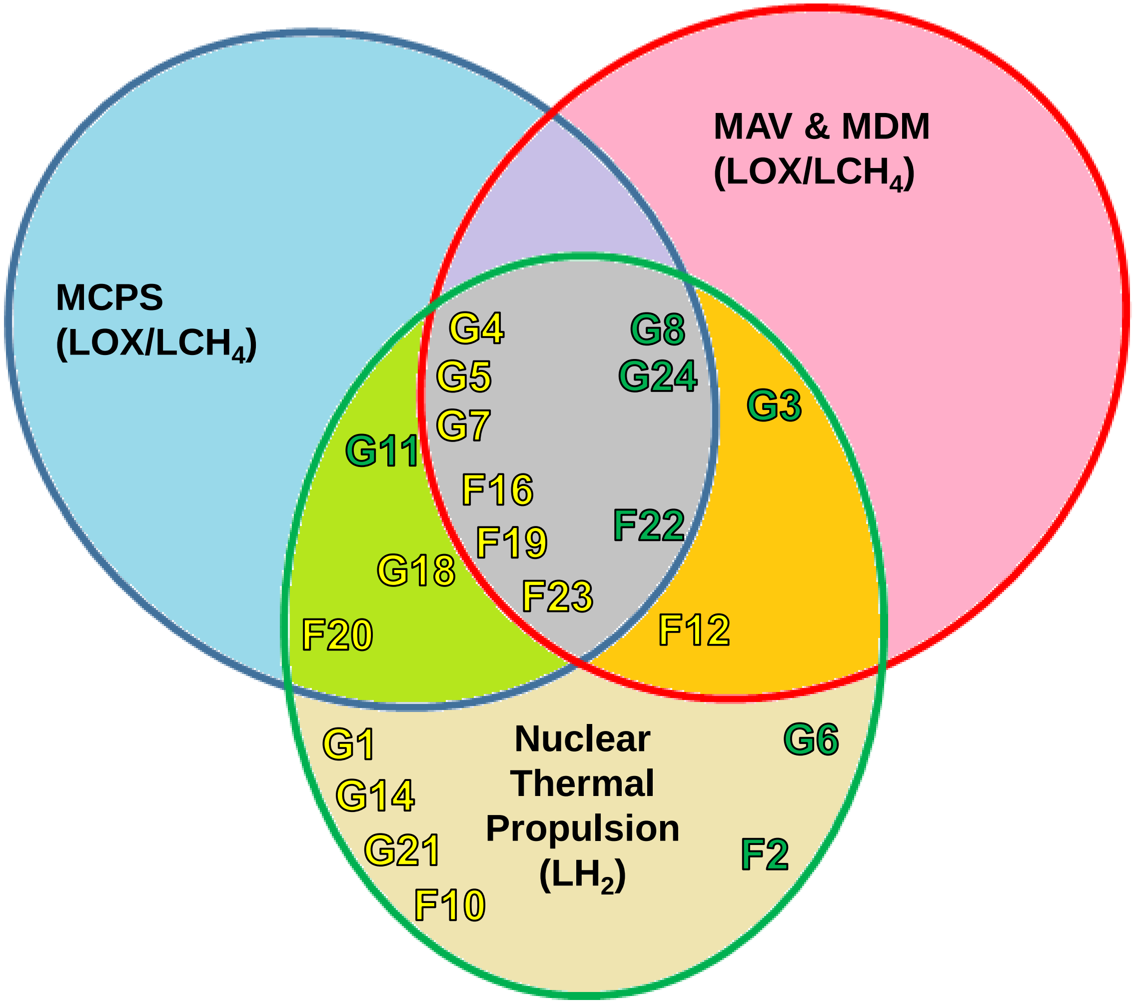
Nuclear Thrust	Burn 1	Burn 2		Burn 3	Burn 4	Totals	
Thrust Time (minutes)	5	12	minutes	7.5	2.5	27	minutes
Start up (minutes)	1	1	minutes	1	1	4	minutes
Cooling Time (Hours)	15.4	30	hours	21	9.3	75.7	hours

(yellow) This indicates Tank is Empty or not required

- **Mission Elapsed Time includes aggregation**
- **Inline Tank 3 spends 4 years in orbit with Hydrogen in it**
- **Quiescent CFM (100 X Days), Nuclear Engine Hot-Fire (Minutes), Reactor Cool Down (Hours)**
- **This analysis assumes Passive CFM is optimized, Active Cooling (Cryocoolers) are utilized and Low Leakage, Long Duration Cryocouplers and Valves are utilized to achieve “near zero” losses.**

NTP Specific CFM Elements Across Multiple Propulsion Pieces

Nuclear Thermal Propulsion



Technologies	Number
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
Thermodynamic 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
Composite Tanks	26

- **Specific to Hydrogen Based NTP**
- **"G" denotes ground testing required to TRL 6**
- **"F" denotes flight demo required to TRL 6**

- **Enhancing** (yellow)
- **Enabling** (green)

CFM Technology Needs (1/2)

Technology	Nuclear (LH2)	In-space Stage (LCH4/LO2)	Ascent Stage (LCH4/LO2)	Descent Stage (LCH4/LO2)	ISRU based System (production) (LO2)	Lunar Aggregation (no production)
Advanced External Insulation	Potential					
Autogenous Pressurization	Baseline (colored)	Potential (colored)	Potential (colored)			Baseline (colored)
Automated Cryo-Couplers	Baseline		Baseline		Potential	Baseline
Cryogenic Thermal Coating	Potential	Potential	Potential	Potential		Potential
Helium Pressurization	Potential	Baseline (colored)	Baseline (colored)	Baseline (colored)		Potential (colored)
High Capacity, High Efficiency Cryocoolers 20K	Baseline					Baseline
High Capacity, High Efficiency Cryocoolers 90K	Potential	Baseline	Baseline	Baseline	Baseline	Baseline
High Vacuum Multilayer Insulation	Baseline	Baseline		Baseline	Potential	Baseline
Liquefaction Operations					Baseline	Potential
Liquid Acquisition Devices	Potential (colored)	Baseline (colored)	Baseline (colored)	Baseline (colored)		Baseline (colored)
Low Conductivity Structures	Potential	Baseline				Baseline
MPS Line Chilldown	Potential (colored)		Baseline (colored)	Baseline (colored)		Baseline (colored)
Para to Ortho Cooling						?

Colored boxes need to fly to get to TRL 6 (colored)
Potential for Architecture Enhancement (Potential)
Currently Listed in Architecture Baseline (Baseline)

W. Johnson & J. Stephens "Cryogenic Fluid Management Roadmapping Exercise" Updated July 26th, 2018

CFM Technology Needs (2/2)

Nuclear Thermal Propulsion

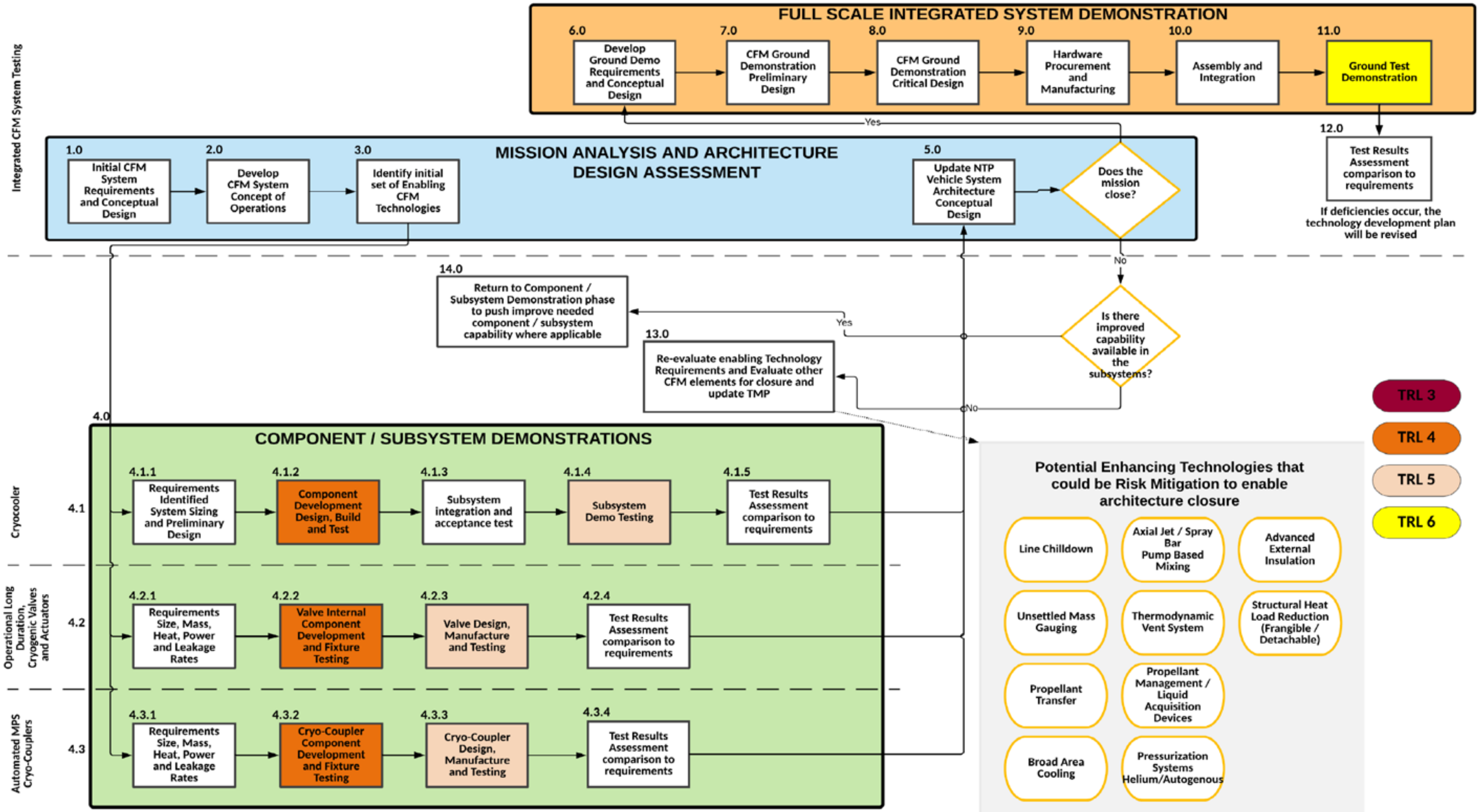
Technology	Nuclear (LH2)	In-space Stage (LCH4/LO2)	Ascent Stage (LCH4/LO2)	Descent Stage (LCH4/LO2)	ISRU based System (production) (LO2)	Lunar Aggregation (no production)
Propellant Densification	[orange flag]					
Propellant Tank Chilldown		(colored) [orange flag]				(colored) [green flag]
Pump Based Mixing	(colored) [orange flag]	(colored) [green flag]	(colored) [green flag]	(colored) [green flag]		(colored) ?
Soft Vacuum Insulation			[green flag]	[green flag]	[green flag]	
Structural Heat Load Reduction	[orange flag]	[orange flag]				[green flag]
Thermodynamic Vent System	(colored) [orange flag]	(colored) [orange flag]				(colored) ?
Transfer Operations	(colored) [orange flag]	(colored) [orange flag]			[orange flag]	(colored) [green flag]
Tube-On-Shield BAC	[orange flag]					[orange flag]
Tube-On-Tank BAC	(colored) [green flag]	(colored) [green flag]	(colored) [green flag]	(colored) [green flag]	[green flag]	(colored) [green flag]
Unsettled Liquid Mass Gauging	(colored) [orange flag]	(colored) [orange flag]	(colored) [green flag]	(colored) [green flag]	[orange flag]	(colored) [green flag]
Valves, Actuators & Components	[green flag]	[green flag]	[green flag]	[green flag]	[green flag]	[green flag]
Vapor Cooling						?
Composite Tanks						

Colored boxes need to fly to get to TRL 6 (colored)
Potential for Architecture Enhancement [orange flag]
Currently Listed in Architecture Baseline [green flag]

W. Johnson & J. Stephens "Cryogenic Fluid Management Roadmapping Exercise" Updated July 26th, 2018

NTP CFM Tech Maturation Plan

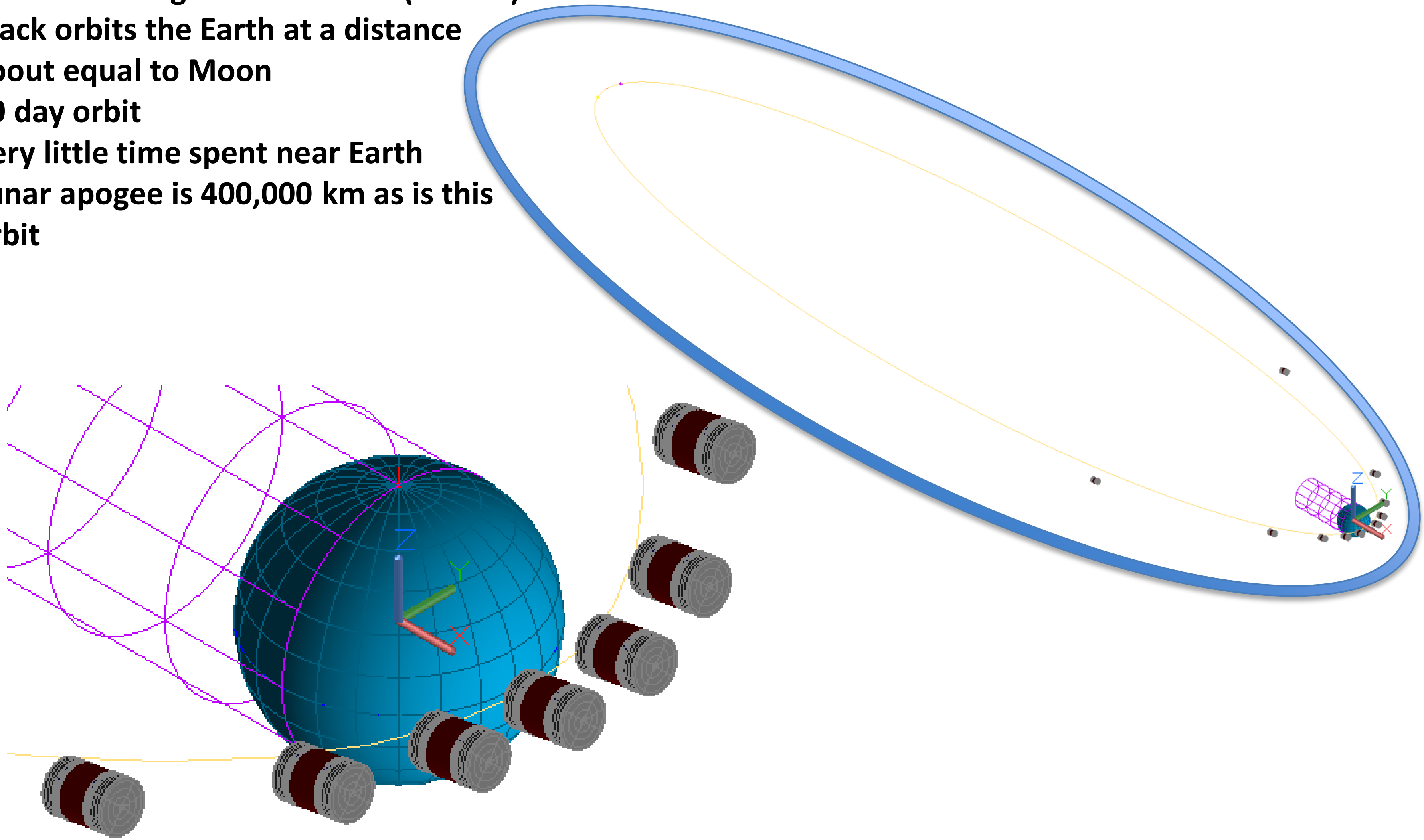
Nuclear Thermal Propulsion



Lunar Distance High Earth Orbit

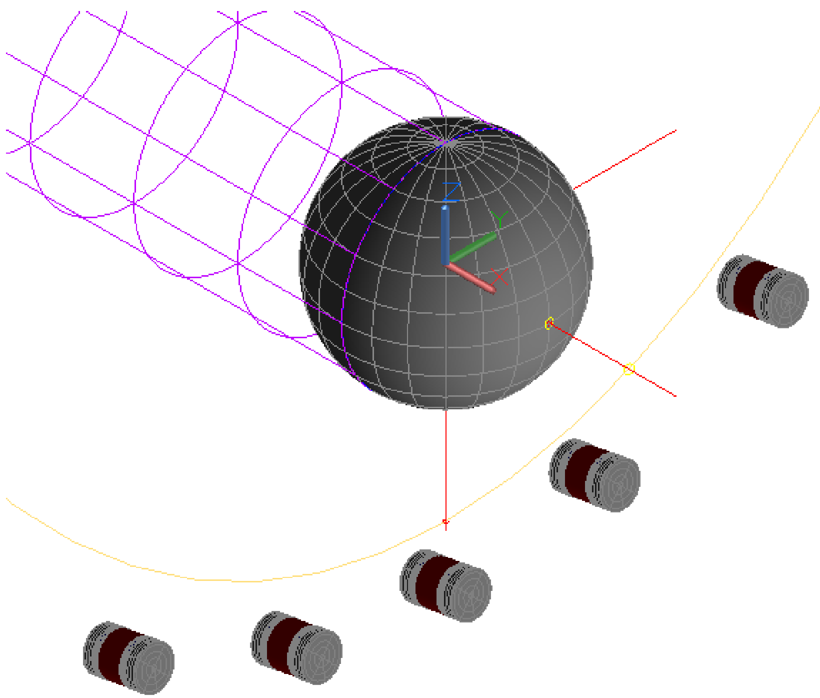
Lunar Distance High Earth Orbit – (LDHEO)

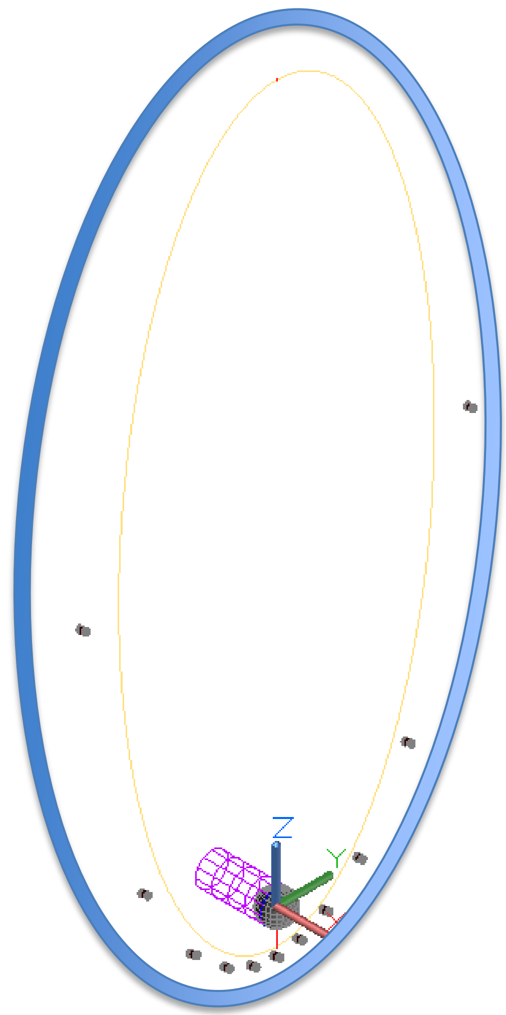
- **Stack orbits the Earth at a distance about equal to Moon**
- **10 day orbit**
- **Very little time spent near Earth**
- **Lunar apogee is 400,000 km as is this orbit**



Near Rectilinear Halo Orbit – (NRHO)

- **Aggregation in NRHO**
- **Elliptical Orbit (very little time near the moon)**
- **Orbital Period: 6 to 14 days**
- **70,000 km x 2,000 km**



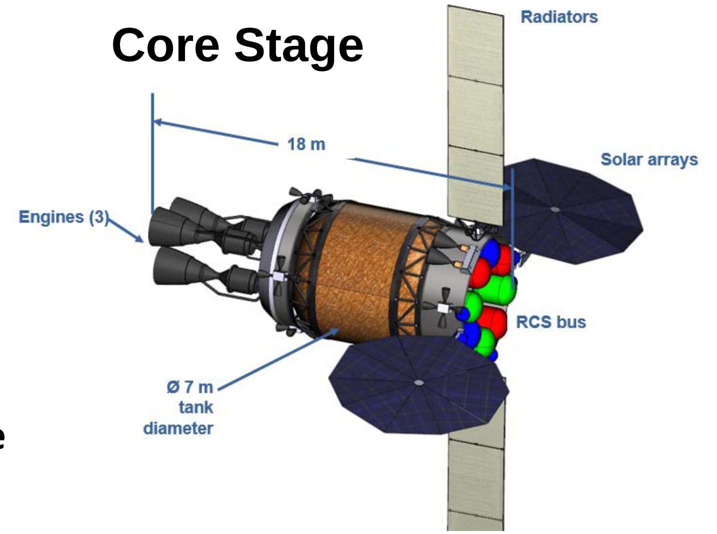


MSFC Advanced Concepts Office NTP Vehicle Concept

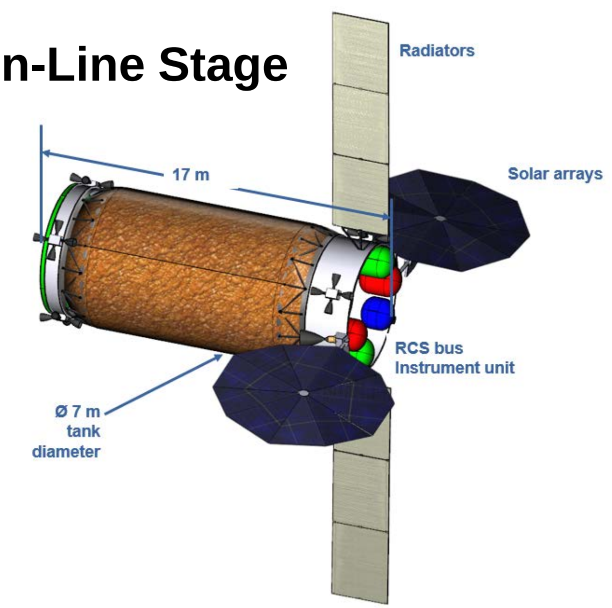
Nuclear Thermal Propulsion

- **Active CFM heat collection via Broad Area Cooling (BAC) tubing networks on LH2 tanks**
- **0.75" SOFI on LH2 tanks**
- **MLI, 40 layers (ε* = 0.0005 to 0.0022) on LH2 tanks**
- **MLI, 3 layers (ε* = 0.005) on LH2 tanks support structure**
- **Tank support structure strut/skirt combination**
  - **Struts: S-Glass shank with Titanium inserts**
  - **Skirts: Al-2219**
- **Avionics/Power heat collection via pumped cooling loops**
- **Heat rejection via double-sided composite heat pipe radiators**

Core Stage



In-Line Stage



Environmental Heating of Cryogenic Tanks -Aggregation-

Nuclear Thermal Propulsion

Environmental heating rates (Watts)

tank	orbit	composite struts	aluminum skirt	titanium skirt	with the MLI on skirts removed		
					composite struts	aluminum skirt	titanium skirt
Core Tank	NRO	51.7	62.2	52.0	178.6	1,094.1	189.9
	LDHEO	54.0	67.6	52.4	169.4	1,043.1	179.3
	LEO beta=0	208.4	844.1	205.5	674.9	3,329.5	724.8
	LEO beta=70	201.4	758.1	199.8	697.8	3,416.2	749.4
In-Line Tank	NRO	43.9	59.1	51.7	187.4	813.1	163.1
	LDHEO	41.5	53.8	48.8	177.3	769.8	153.4
	LEO beta=0	125.7	162.0	135.5	712.6	2,840.7	685.9
	LEO beta=70	127.5	172.3	141.9	735.7	2,916.7	711.3

NOTE: 44% margin added to these results

Model generated by Steven Sutherlin
NASA/MSFC/ED04

Eric T. Stewart
NASA/MSFC/ER43
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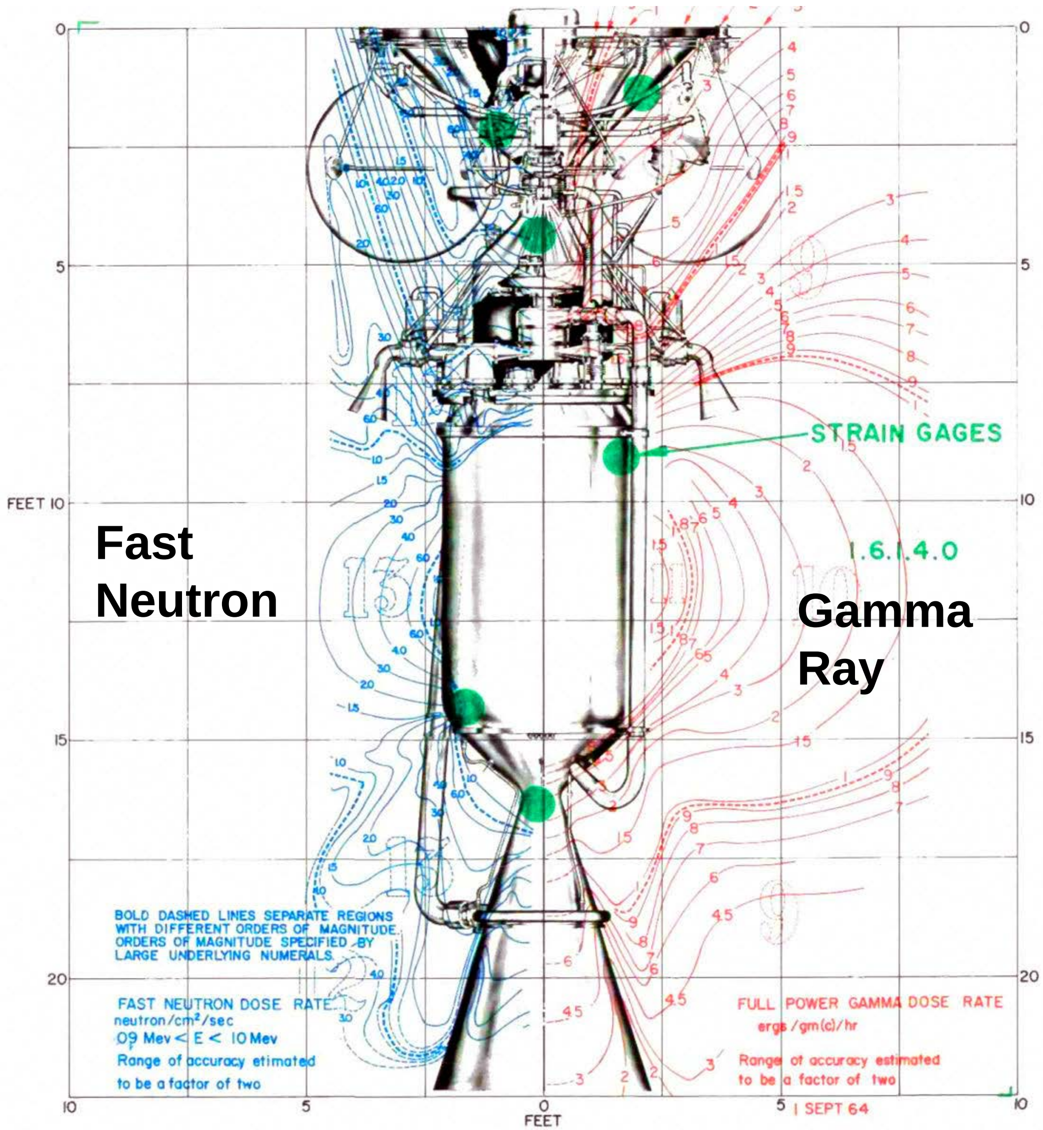
- **Multiple 20 K, 20 W cryocoolers (Two Fault Tolerant)**
  - **Core Tank: 6 cryocoolers (maximum of 4 operating)**
  - **In-line Tank: 5 cryocoolers (maximum of 3 operating)**

Nuclear Heating (Liability)

Nuclear Thermal Propulsion



- Image is measured NERVA data
- When Reactor is "Hot", it generates Gamma ray & Fast Neutron Heating
- Hydrogen absorbs both very well. ☹
- Shielding is difficult or expensive (heavy)
- Core tank is most effected

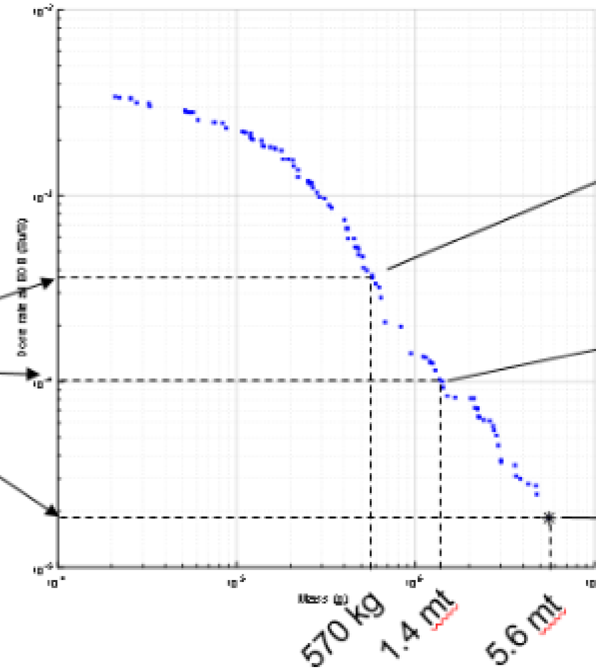
Nuclear Heating

Nuclear Thermal Propulsion

- Calculated using optimization model that factors in desired crew dose rates in habitat
- Shield sizes and materials optimized using a genetic algorithm
- Conservative estimate is ~3 mT (1mT per engine), results in ~10 kW heating per engine

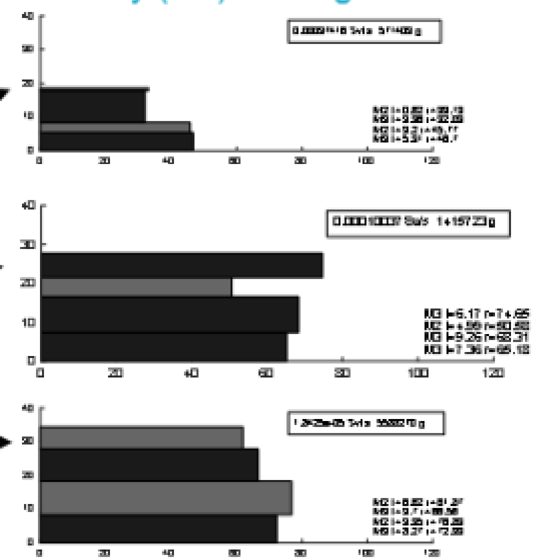
Scaled dose-rate to Integrated dose, approximated from time-series calc

Desired Integral Dose (Sv)	Required EOB Rate (Sv/s) per engine
0.2 (20 rem)	3.9E-4
0.5 (5 rem)	9.6E-5
0.01 (1 rem)	1.9E-5



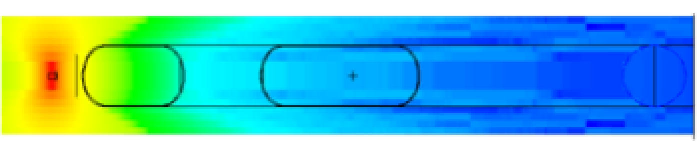
Masses are per-engine

Black (M3) = Boron Carbide
Grey (M2) = Tungsten



Profiles of radius and thickness (cm)

Assumes:
- 3 Engines at 560 MW
- Dose rates observed at 80m
- No other shielding except LH2/tank



NOTE: Low sample size in optimization case (coarse calculation). Actual masses will be further reduced from those shown here.

Nuclear Heating

- **Conservative estimate is ~3 mT (1mT per engine), results in ~10 kW heating per engine**
  - **While this is significant heating, it is not enough heating to self pressurize the tank.**
  - **The amount of energy required to pressurize the tank is on the order of 400kW and will be achieved by autogenous pressurization during engine hot-fire.**
  - **Analysis of a 2-Phase boost pump currently in work. There appears to be no technical challenges with a boost pump and main pump working together.**

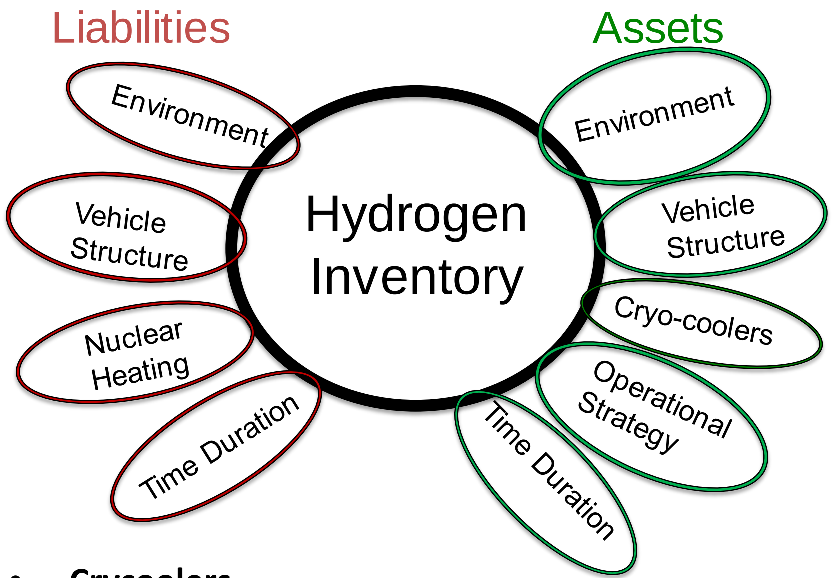
- **The bigger problem for CFM maybe the latent heat in the tank and the balance of LH2 in the core tank.**

- **The reactors (engines) run for just a few minutes at a time (5 to 12 minutes), but require pulse cooling for hours afterwards; up to 36 hours for the longer runs.**

- **The amount of LH2 that is required for cooling will vary inversely to time; 3 to 7% of the LH2 mass consumed during each burn.**

Effects on Hydrogen Inventory

Nuclear Thermal Propulsion



- **Crycoolers**
  - **Tank pressure control without loss of propellant**

- **Operational Strategy**
  - **The flexibility to manage how/when hydrogen flows from tank-to-tank is an asset.**
  - **Cascade method is currently baselined, but is probably not optimal.**

- **Time Duration**
  - **Tanks are in NRHO for extended periods of time**
  - **Significant time between hot-fires to recondition propellant**

- **Environment**
  - **Sun, Moon and Earth are all heat sources**
  - **Aggregation in NRHO requires liquid hydrogen to be stored for three years. However, NRHO and LDHEO are thermally "benign" relative to LEO.**
  - **Transport environment is cold.**

- **Vehicle Structure**
  - **Skirts: Structure that interfaces with the tank**
  - **Struts: Can be used with skirts and designed for extremely low thermal conductivity**
  - **MLI on propellant tank (~40 layers)**
  - **MLI on vehicle structure**
  - **Tank penetrations**
    - **An be a significant source of heat**
    - **Must be insulated**

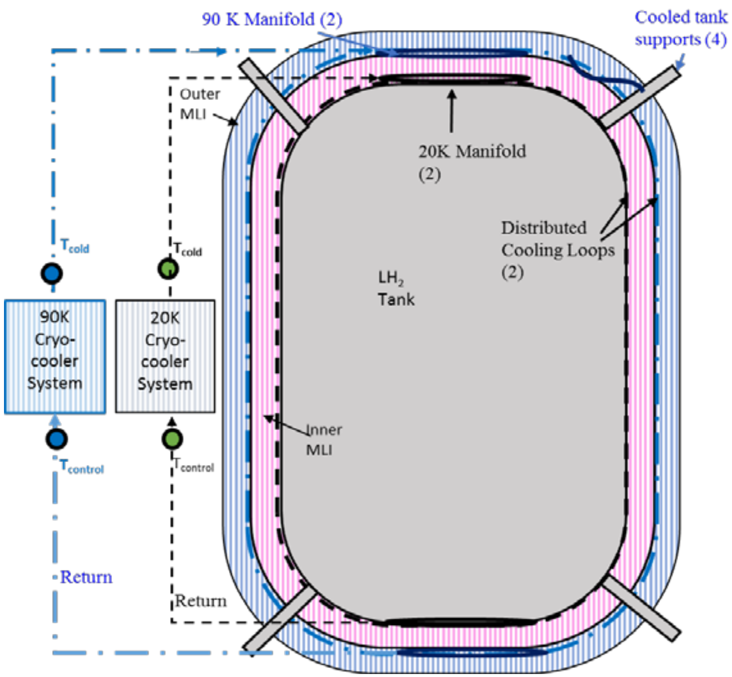
- **Nuclear Heating**
  - **Requires shielding to mitigate**
  - **Possible fluid dynamic issues internal to propellant tank**

Summary – CFM for NTP

- **CFM for NTP is a challenge**
  - **Long duration mission (years!!!)**
  - **Nuclear Heating**
  - **Technology development for some elements are needed.**
  - **Active cooling is needed to enable mission**
    - **Requires both Mass and Power**
- **Aggregation currently in NRHO**
  - **Fairly benign environment thermally relative to LEO**
  - **Heat loads associated with the baseline structure are manageable**
    - **Six Cryocoolers on Core Tank**
    - **Five Cryocoolers on each Inline Tank**
- **Heat loads during ground operations and during ascent are currently being evaluated**
- **Operational strategies provide many "knobs" to turn to maximize the LH2 life, but are very nascent at this time.**
  - **Example: Cascade Flow vs Run Tank method**

Trade Studies

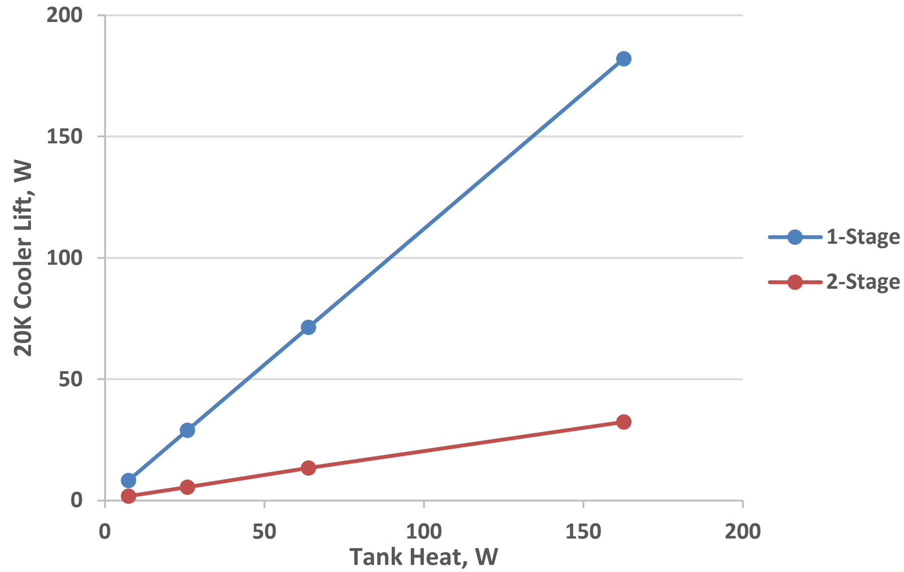
- **Two-Stage Cooling Trade – Glenn Research Center**
  - **Evaluates the potential Mass and Power savings with two-stage cooling vs one-stage**



  - **With two-stage cooling, 90K cryocoolers are used for heat intercept to minimize the requirements on the 20K cryocoolers**
  - **90K cryocoolers have lower Specific Mass and Specific Power then 20K cryocoolers**
  - **Results from a recent study indicate two-stage cooling trades favorably for NTP**
    - **D. Plachta, J. Hartwig, J. Stephens and E. Carlberg, "Zero Boil-Off System Trades Applied to Nuclear Thermal Propulsion", 20th International Cryocooler Conference, June 18th-21st, 2018 in Burlington, VT.**

Two Stage Cooling for LH_2

- **Tank heat load plotted vs. 20 K cooler lift for 2 Stage and 1 Stage concepts**
  - **Size of 20 K cooler is substantially reduced for 2 Stage concept**



- **Recent NTP study found significant advantages to 2-stage cooling**

	Temp., K	Lift, W	Active System Mass, kg	Input Power, W
20K Class	24.2	16.5	275	1150
90K Class	55	94	192	880
Total			*467*	*2030*
Single 20K Class Stage Cooling	*24.2*	*114*	*1500*	*7000*

Analysis Developments

CAT Improvement	Specification
20K-20W Cryocooler Developments (24.2 K LH2 storage temp)	50 W/W Specific Power, 3.7 kg/W Specific Mass
90K-150 W Cryocooler Development	9W/W Specific Power, 0.36 kg/W Specific Mass
Cooling Strap Contact Resistance	10 K/W
Broad Area Cooling Pressure Drop	Tube gas velocity and pressure drop found
Tank Insulation Seam Heat	Open butt seam assumed with 3mm gap.
Tank Insulation Pin Heat	1 pin every 30 cm, Nylon
Penetration to tank MLI seam	Q estimated from parametric relationship assuming MLI butt with Cryolite
Insulation on structure and penetrations	20 layers of MLI assumed, Modified Lockheed Eqn. with scale factor 6 used

- **An update to ZBO modeling is complete for NTP, LH_2 storage**
- **Thermal control system mass is compared for passive, 1 Stage and 2 Stage concepts**
- **For these large tanks, active cooling saves mass after ~ one month in LEO**
- **Two stage cooling saves mass and power, while greatly reducing 20K cryocooler requirement**

Trade Studies

- **Potential use of Cryogenic Thermal Coatings for NTP – Kennedy Space Center**
  - **Developed a new concept where a combination of “solar white” and MLI could yield an improved flexible insullative radiation shield.**

- **Benefits of loading densified hydrogen for NTP – Kennedy Space Center**
  - **Large thermal capacitance of densified hydrogen allows the hydrogen to be held for a longer time before Active Cooling is needed.**

Forward Work

- **Evaluate Structural options for thermal optimization (Design → Structural Analysis → Thermal Analysis)**
  - **Struts vs Skirts**
  - **Aluminum vs Titanium vs Composite**
  - **Include tank penetrations (Fill/Drain, Pressurization, Vent)**

- **Conduct a Thermal "Soak Back" Analysis**
  - **Heat conducted through the structure and penetrations during engine hot-fire and reactor cool down.**

- **CFD Analysis to evaluate the behavior of the Core Stage propellant during engine hot-fire.**

- **CFD Analysis to evaluate the feasibility of using Tube-On-Tank Broad Area Cooling integrated with cryocoolers for pressure control in micro-g – Glenn Research Center**