WWW.NASAWATCH.COM

Propellant Depot Requirements Study Status Report

HAT Technical Interchange Meeting

July 21, 2011

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Propellant Depot Requirements Study Approach

- Team committed to finding opportunities for future exploration missions/architectures to benefit from commercial involvement to improve affordability and stimulate industry
- Developing refueling- based architectures to satisfy currently planned HAT DRMs using different CONOPS
- Comparing four major architecture approaches:
  - Baseline >100MT SDV HLLV, no refueling
  - > 100MT SDV HLLV, with re-fueling, including sub-orbital burn CPS/Depot
  - No HLLV prior to human Mars, with re-fueling using current and planned commercial launch vehicles and sub-orbital burning CPS/Depot
  - Commercial-derived > 100MT triple-core HLLV, single core < 50MT, phased development, sub-orbital burn CPS/Depot
- Apples to apples LCC/LOC/LOM/programmatic risk FOM assessment
- Consistent groundrules/assumptions and performance/cost models
- Use commercial costs (w/ margins) for commercial elements
- Free exchange of data/models w/HAT, regular coordination meetings

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Why Examine Propellant Depots Without HLLVs?

- Large in-space mission elements (inert) can be lifted to LEO in increments on several medium-lift commercial launch vehicles (CLVs) rather than on one Heavy Lift Launch Vehicle (HLLV)
- Over 70 percent of the exploration mission mass is propellant that can be delivered in increments to a Propellant Depot and transferred to the in-space stages
- Saves DDT&E costs of HLLV
- Low-flight-rate HLLV dominated by high unique fixed costs. Use of CLVs eliminates these costs and spreads lower fixed costs over more flights and other customers.
- Use of large re-fueled cryo stages saves DDT&E/ops costs for advanced propulsion stages (e.g., SEP)
- Provides opportunity for more easily integrated commercial and international partner mission participation

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Study Status

- Defined depot/CPS-based architectures to perform NEA and lunar missions (DRMs 34A/B and 33C/D) using apples-to-apples HAT groundrules and assumptions
  - Consistent in-space elements, margins, delta-Vs, cost tools, masses, etc…
- Examined launching on Falcon Heavy, Delta IV Heavy, international vehicles, and a mixed fleet of commercial launchers
- Examined O2/H2 and O2/RP depot/CPS
- Examined single- and two-stage CPS for NEAs
- Completed DDT&E and recurring cost analysis and generated LCC charts for lunar and NEA scenarios
- Began reliability, LOM and availability analysis
- Performed launch rate and capacity analysis
- Performed sensitivity analysis to launch price and other cost assumptions
- Developed technology requirements and development plan

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Examples of Top-Level Performance Groundrules/ Assumptions (Consistent with HAT)

- Nominal depot orbit of 400 km circular, 28.5 deg. Inclination.
- Nominal dedicated depot life of 10 years after which de-orbit and replacement is required.
- Depot assumed to have maximum reasonable commonality with in-space cryogenic propulsion stage (CPS)
- Depot is compatible with multiple propellant delivery vehicles
- Depot is capable of holding enough propellant, with contingency, to re-fuel and top-off the largest CPS for a given mission load
- Level I reserve of 5% of wet payload stack/adapter mass
- 10% payload margin on all launch vehicle payload predictions
- Launch vehicle adapter mass of 2.5% of wet payload stack mass
- 5% flight performance reserve on delta-Vs
- Dry Mass Growth Allowances (MGA) of 30%
- Qualification of in-space crewed systems requires a minimum of one flight demonstrating full functionality prior to BEO missions

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Examples of Top-Level Cost Groundrules/ Assumptions (Consistent with HAT)

- Using HAT data elements and margins/groundrules where available
  - Currently using HEFT data where HAT data is not yet available
- No benefit taken for bulk buy discounts or lower prices at higher rates
- Extra launch costed for every ten launches, cost of failure
- Extra tanker and flight costed for each mission
- Added Launch Service Program costs onto conservative launch prices
- Added non-recurring costs where additional launch capacity required
- Crew launched on commercial crew system at marginal cost (not MPCV).
- High level of commonality between Depot and CPS, using existing engines
- CPS/Depot government owned and operated, traditional procurement
- Commercial launches and propellant supply Vehicles (PSVs), procured under Other Transaction Authority (e.g., COTS)
- Program Integration as a fixed cost consistent with HAT/HEFT
- Project Insight /Oversight, Mission/Flight Ops, and Ground/Launch Ops estimated using CERs consistent with HAT/HEFT percentages except for the commercial tankers and their launchers, which were fixed.

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

NEA Missions With Depot/CPS Using Falcon Heavy LV

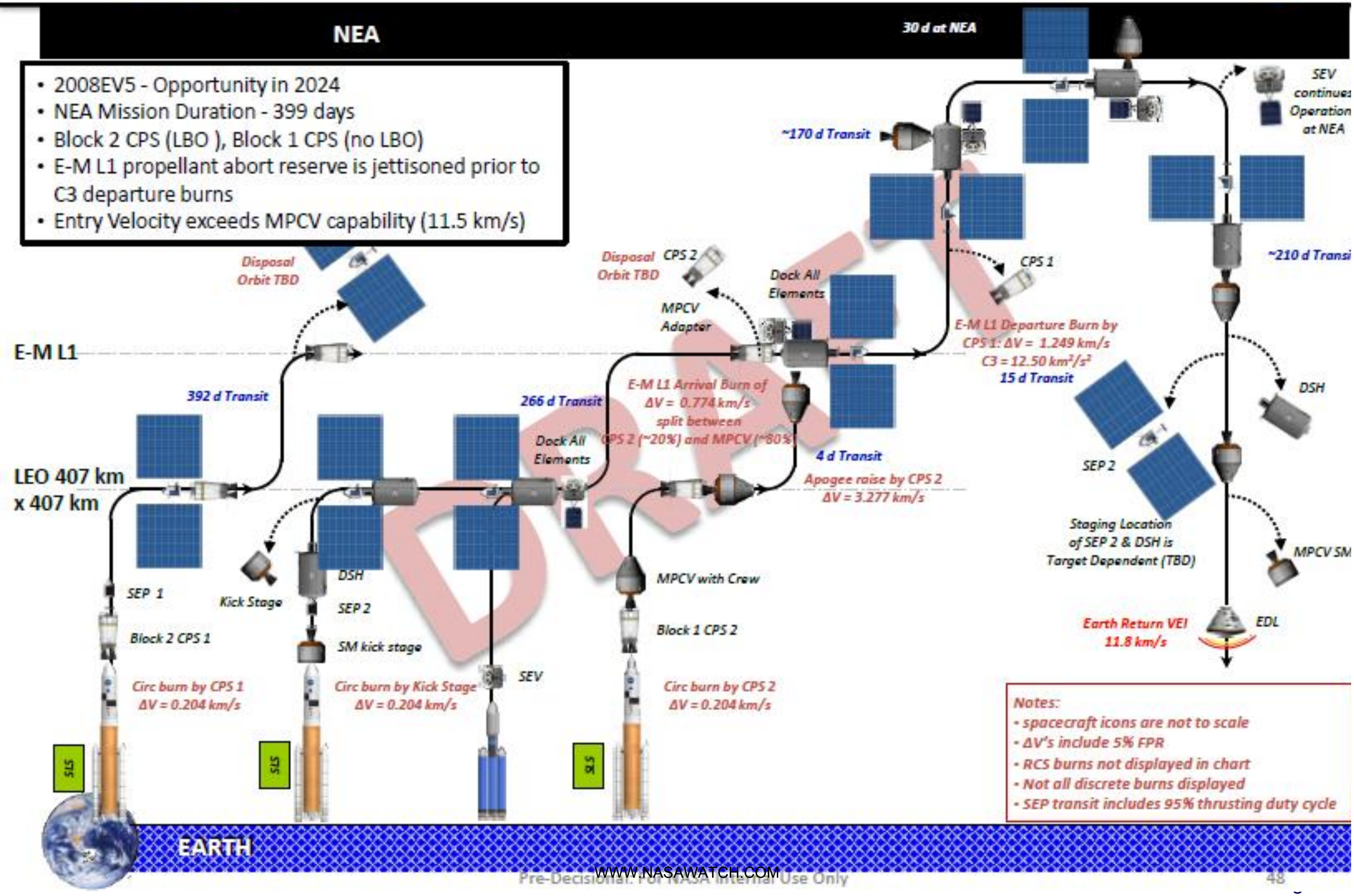
WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Full Capability, High Energy NEA (2008EV5) with SEP

NEA_FUL_1A_C11B1 (DRM 34B)

- 2008EV5 - Opportunity in 2024
- NEA Mission Duration - 399 days
- Block 2 CPS (LBO), Block 1 CPS (no LBO)
- E-M L1 propellant abort reserve is jettisoned prior to C3 departure burns
- Entry Velocity exceeds MPCV capability (11.5 km/s)



DRAFT

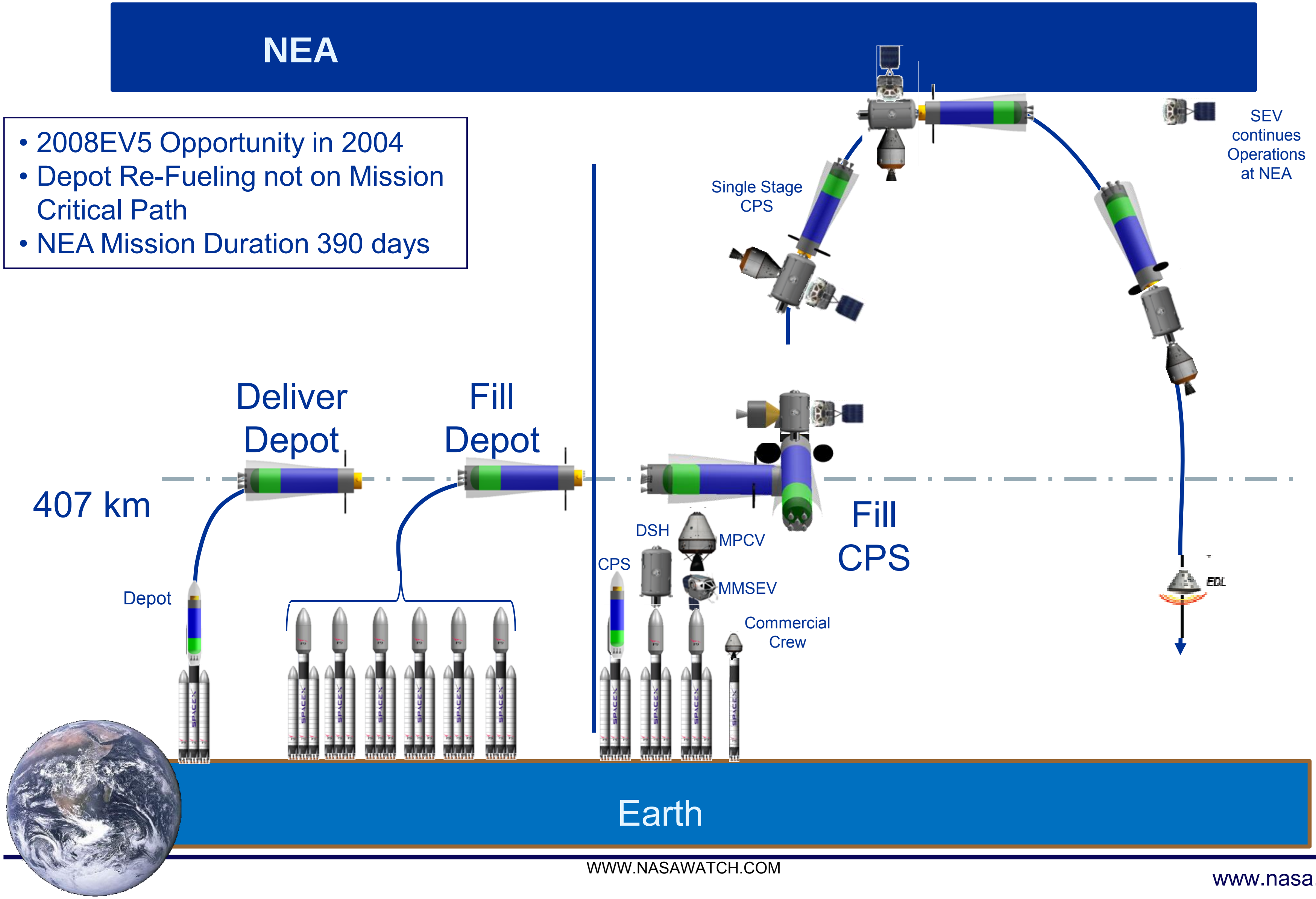
Notes:
- *spacecraft icons are not to scale*
- *ΔV's include 5% FPR*
- *RCS burns not displayed in chart*
- *Not all discrete burns displayed*
- *SEP transit includes 95% thrusting duty cycle*

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 34B w/ 50MT Falcon Heavy + Propellant Depot/CPS

- 2008EV5 Opportunity in 2004
- Depot Re-Fueling not on Mission Critical Path
- NEA Mission Duration 390 days

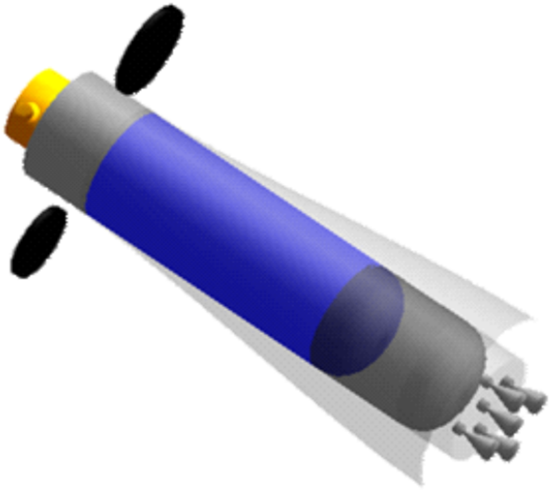


WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

NEA Mission Propellant LO2/LH2 Depot/CPS

DRM34B Depot LOX/LH2



Propellants	**LOX/LH2**
Stage Diameter	**6 m**
Stage Length	**28 m**
Oxidizer Boiloff	**0%/month**
Fuel Boiloff	**0.5%/month**
Sub-orbital T/W	**0.72**
Orbital T/W	**0.20**
Power	**3736 W**
Cryocooler Power	**2736 W**
Mass Growth, %	**30**
# Engines / Type	**5 RL10 B-2**
Engine Isp (100%)	**464 sec**

	Mass, kg
2. Body Structure	8,835
3. Induced Environmental Protection	485
5. Main Propulsion	1,764
6. Orient Control Separation	193
7. Prime Power	261
8. Power Conversion and Distribution	52
9. Guidance and Navigation	38
10. Instrumention	32
11. Communication	97
12. Thermal Control	2,193
16. Range Safety and Abort	69
16a. Mass Growth Allowance	4,212
19. Ordanance	20
Dry Mass	**18,252**
21. Residual Propellant	4,616
23. Inflight Losses	30
25a. RCS Propellant	5,938
25. Total Propellant inc Boiloff	230,799
IMLEO	**315,208**

Propellant Burn 1	187,354
Payload Burn 1	55,574
DeltaV Burn 1	4,228
Propellant Burn 2	31,273
Payload Burn 2	55,574
DeltaV 2	1,342
Propellant 3	6,978
Payload 3	48,281
DeltaV 3	395

Description:

The combined propellant depot and CPS stage is capable of holding enough O2 and H2 (225MT) to perform NEA missions requiring up to 7 km/s of delta-V when used as a CPS stage. Both the Depot and CPS have MLI (SOFI for ground hold and 60 layer MLI), cryocoolers, and sunshield. Power is with Ultraflex solar cells.

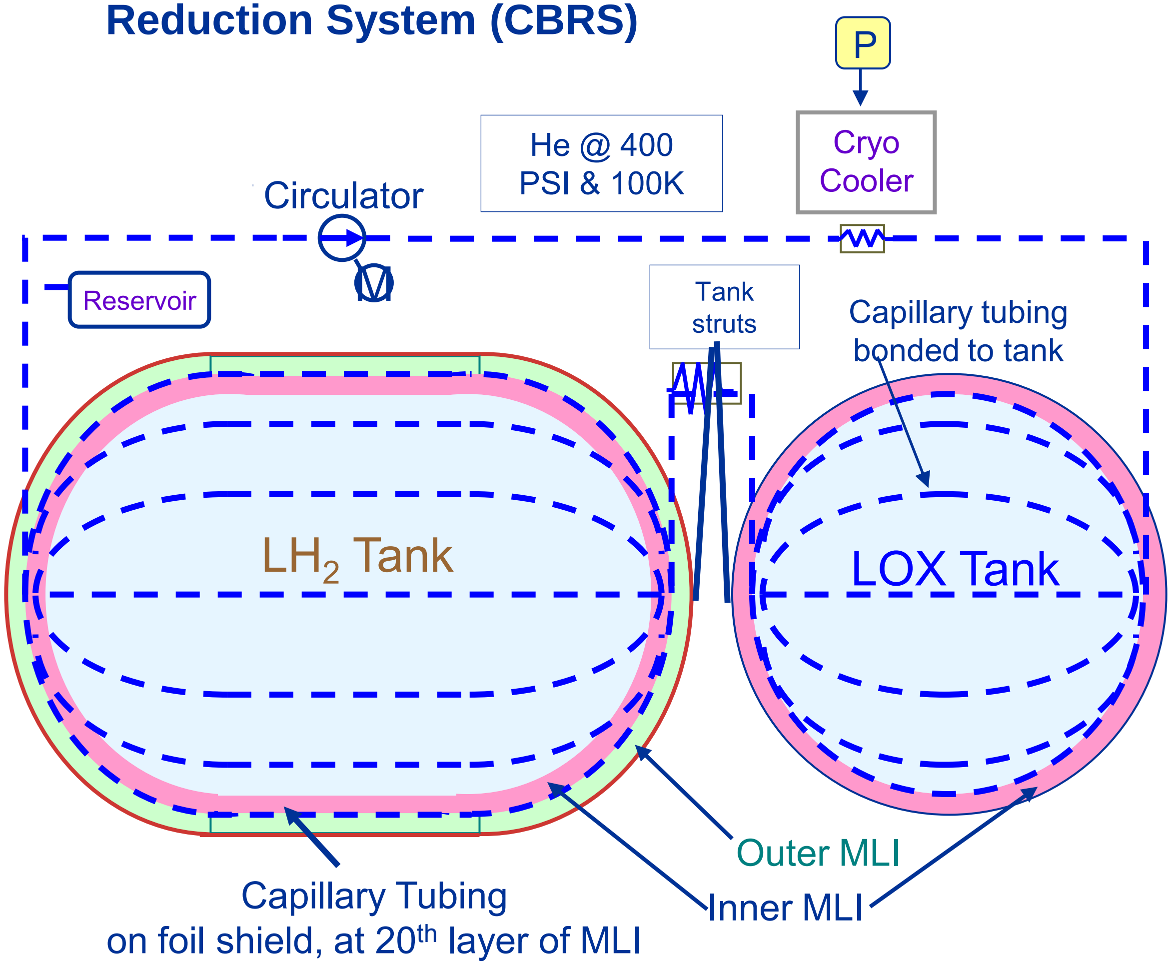
Both the Depot and Depot-Derived CPS can be launched from a Falcon Heavy or Delta IV Heavy replacing the second stage of the launch vehicle and using the RL 10 engines to place itself into a 407 km, 28.5 deg inclination circular orbit.

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Cryogenic Storage Control Technology Approach

Cryogenic Storage Schematic w/ Cryogenic Boil-off Reduction System (CBRS)



CBRS Characteristics:

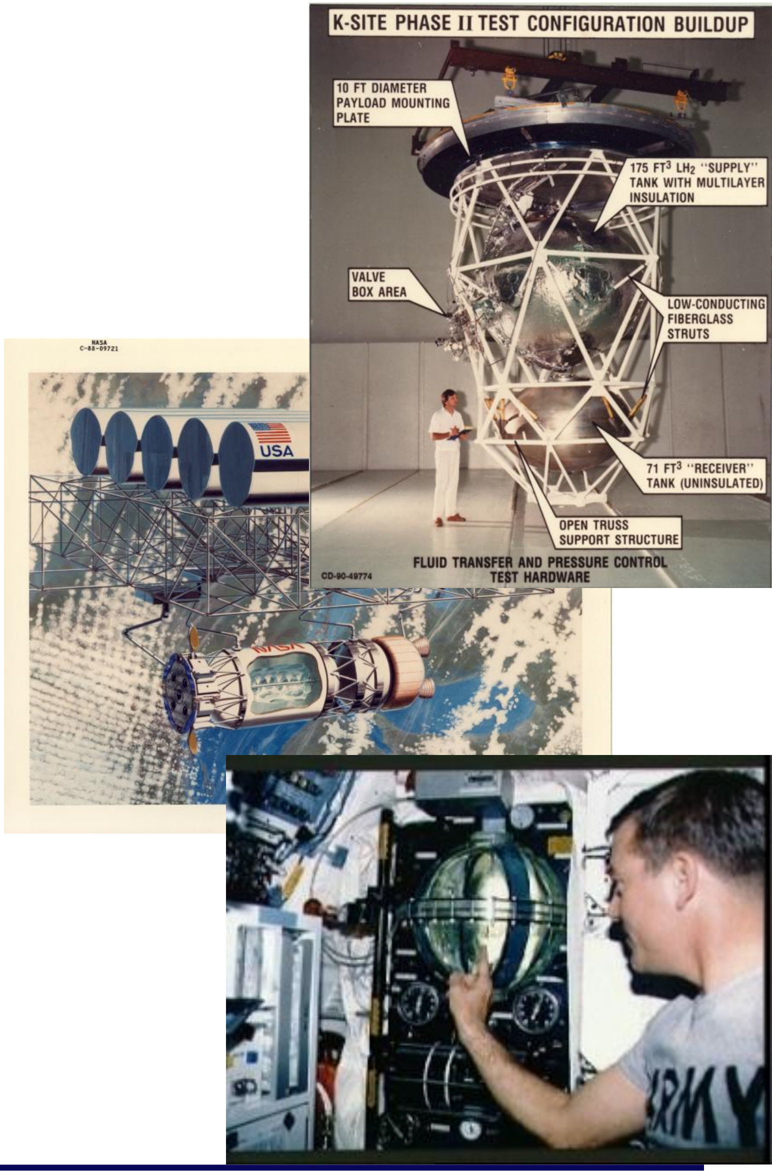
- Efficiently moves heat to cryocooler
  - Used to cool tank struts/ penetrations/ He pressurant bottle
- Integrates LO$_2$ cryocooler with LH$_2$ tank insulation
  - LO$_2$ cryocooler technology is available today
  - LH$_2$ 100K shield reduces hydrogen boil-off by 70%
- One cooler used to cool multiple tanks
  - Incorporates one BAC loop with parallel paths
    - Reduces parts
    - More efficient cooling

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Tank Chill and Fill Technology Approach

- Current baseline approach is to use micro – g thruster settling to acquire propellants and a No-Vent Fill procedure to transfer propellants.
- Recommended approach requires minimal additional hardware
- No Vent Fill
  - Uses evaporative cooling and sub-cooling to chill cryogenic tank and transfer fluid with out venting
  - Demonstrated in 1990's at GRC-PB
- Both micro g settling and No Vent Fill will require proof of concept on Cryogenic Propellant Storage and Transfer technology Demonstrator



WWW.NASAWATCH.COM

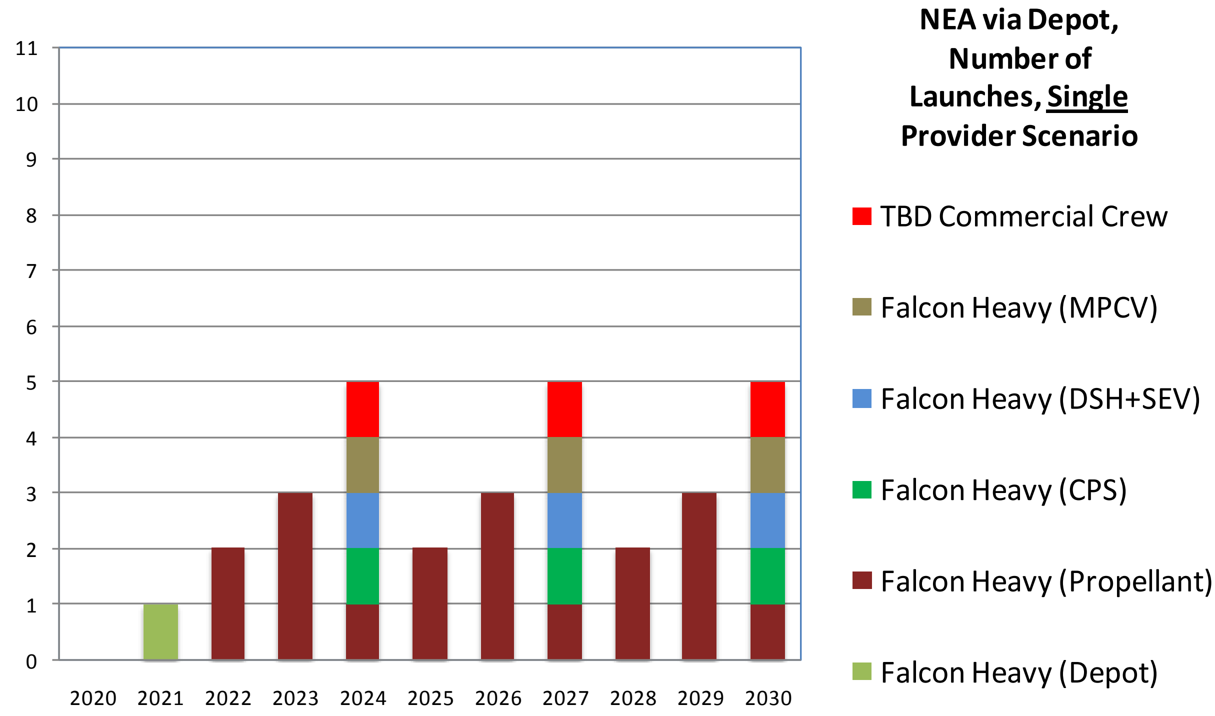
WWW.NASAWATCH.COM

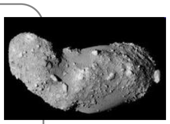
NEA Mission Falcon Heavy Launch Schedule

3 NEA Missions / 27 Launches after Depot Placement

< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

Reserve propellant flights – not shown



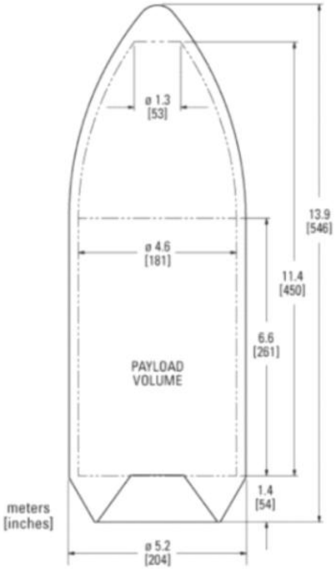


WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Falcon Heavy Propellant Tanker Design

Falcon Heavy Shroud



Propellant Tanker

	Mass, kg
2. Body Structure	2,335
3. Induced Environmental Protection	171
5. Main Propulsion	-
6. Orient Control Separation	66
7. Prime Power	135
8. Power Conversion and Distribution	27
9. Guidance and Navigation	38
10. Instrumention	32
11. Communication	97
12. Thermal Control	938
16. Range Safety and Abort	69
16a. Mass Growth Allowance	1,178
19. Ordnance	20
Dry Mass	**5,106**
21. Residual Propellant	792
23. Inflight Losses	5
25a. RCS Propellant	522
25. Total Propellant inc Boiloff	39,576
Wet Tanker	**47,000**

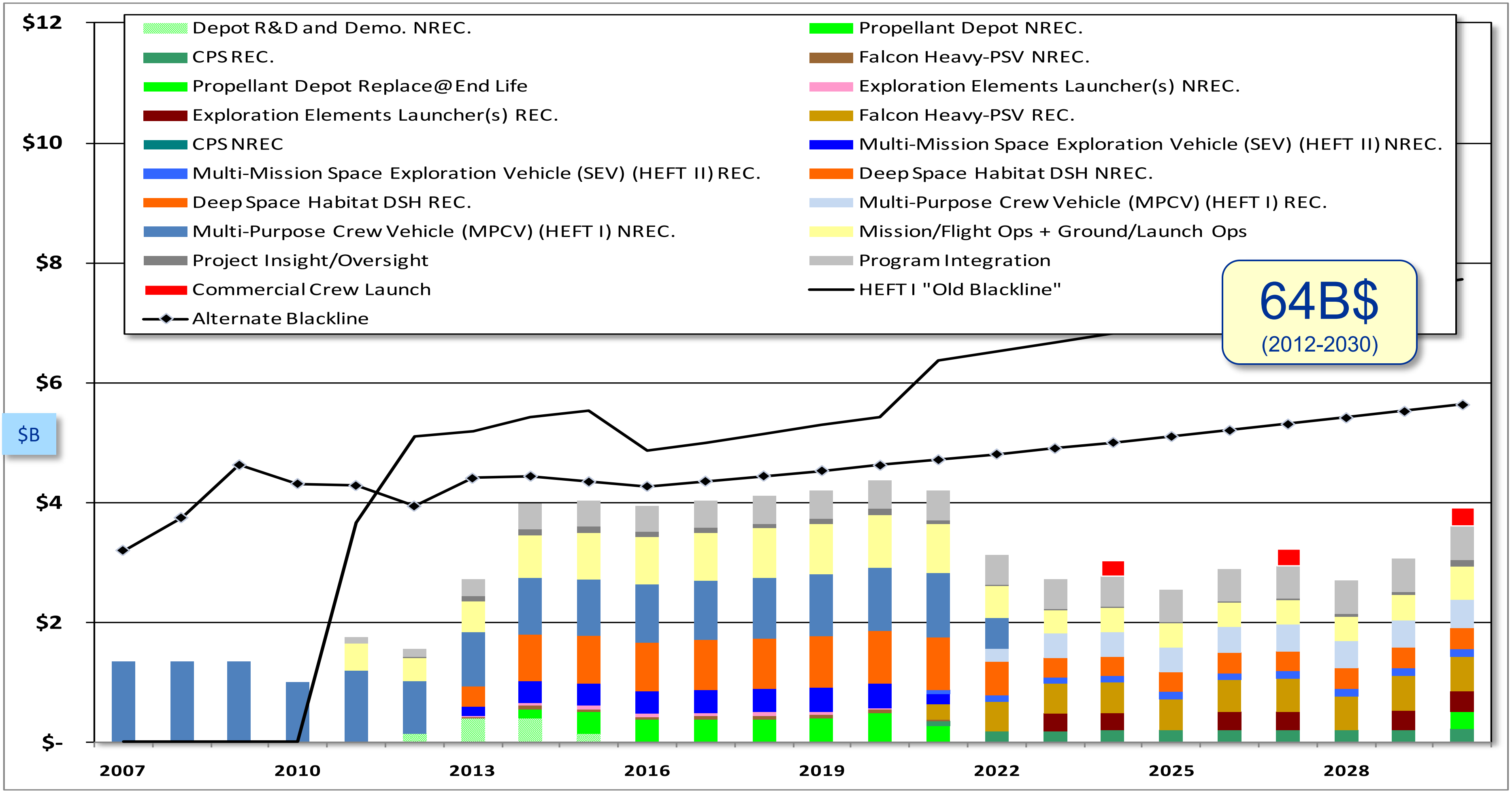
Propellants	LOX/LH2
Stage PMF	0.86
Stage Diameter	4.6 m
Stage Length	11.3 m
RCS DeltaV	200 m/s
Mass Growth, %	30

Description:

The Tanker is sized to be delivered in the Falcon Heavy payload bay. AR&D 200 m/s deltaV included. SOFI and 60 layer MLI is used for thermal control.

WWW.NASAWATCH.COM

Falcon Heavy Based NEA Mission LCC, First Mission 2024, Missions Every 3 Years

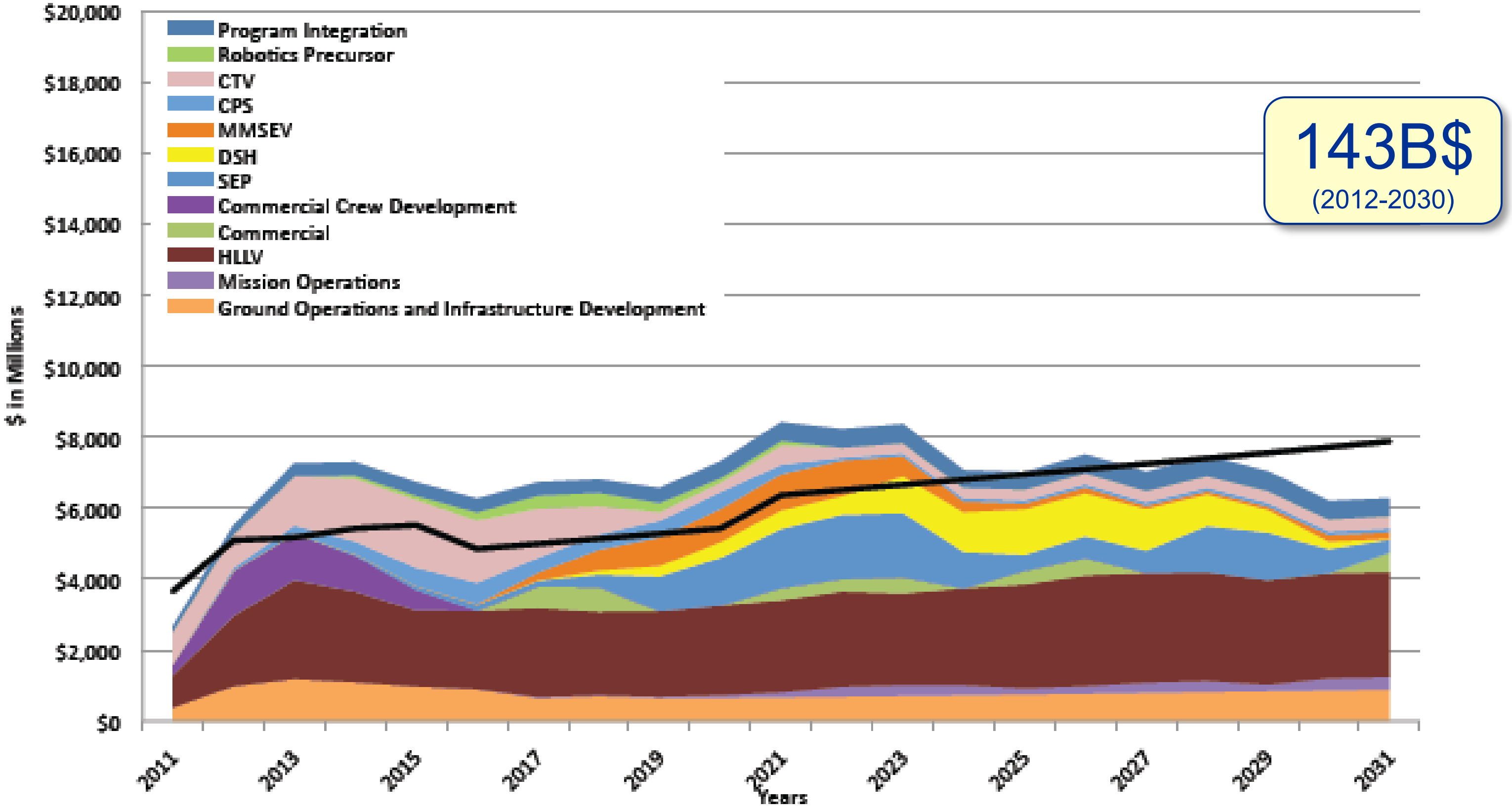


64B$

(2012-2030)

WWW.NASAWATCH.COM

HEFT 1, DRM 4, NEA Mission in 2029



NASAWATCH.COM

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

NEA Mission Observations – Falcon Heavy LV

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 3-5 NEA missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first mission to NEA in 2024, potentially several years earlier than HLLV/SEP-based approaches, meeting President’s deadline and actual availability of NEA 2008EV5
- Launch capacity does not appear to be a major issue
- Dependence on a single CLV and provider likely unacceptable
- Integration of large CPS stage with small-diameter Falcon adds complexity (similar to large fairing Titan IV, but acts as stage)

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

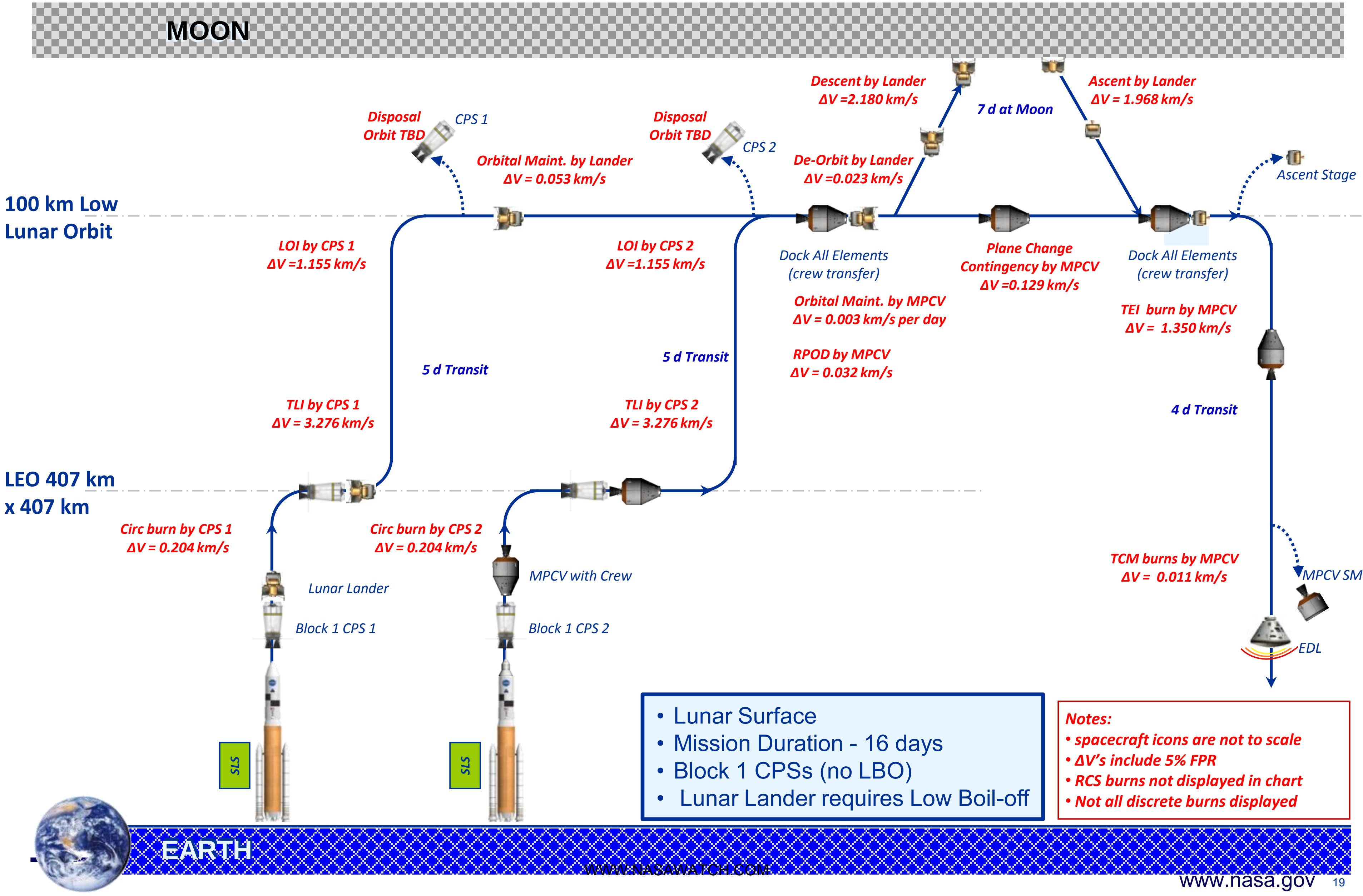
Lunar Missions With Depot/CPS, Using Falcon Heavy LV

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Lunar Surface Sortie Mission - LOR/LOR

LUN_GBL_1A_C11B1 (DRM 33C)



- Lunar Surface
- Mission Duration - 16 days
- Block 1 CPSs (no LBO)
- Lunar Lander requires Low Boil-off

Notes:

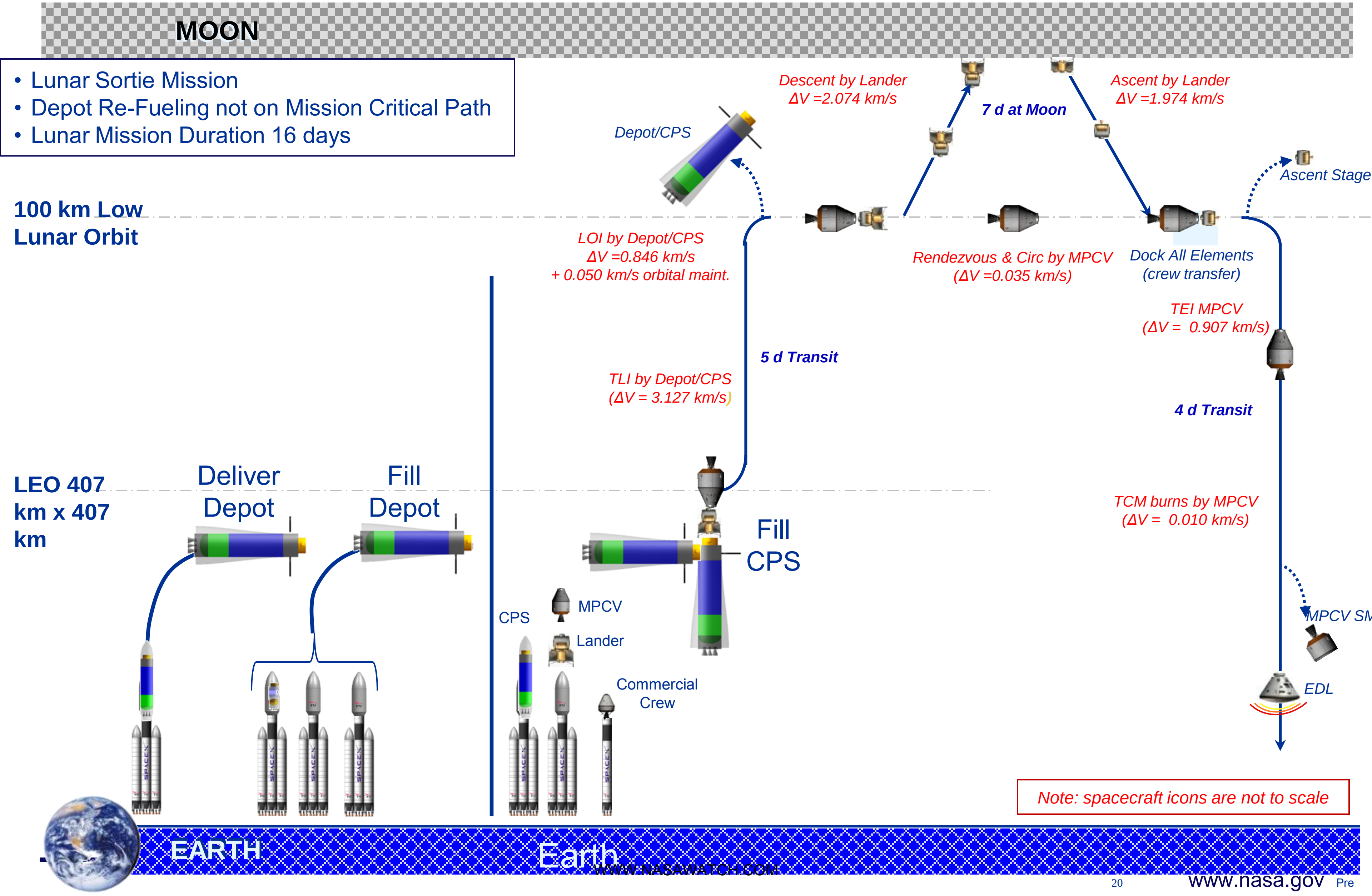
- *spacecraft icons are not to scale*
- *ΔV's include 5% FPR*
- *RCS burns not displayed in chart*
- *Not all discrete burns displayed*

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 33C w/ 50MT Falcon Heavy + Propellant Depot/CPS

- Lunar Sortie Mission
- Depot Re-Fueling not on Mission Critical Path
- Lunar Mission Duration 16 days



MOON

100 km Low Lunar Orbit

Depot/CPS

Descent by Lander
ΔV =2.074 km/s

7 d at Moon

Ascent by Lander
ΔV =1.974 km/s

Ascent Stage

LOI by Depot/CPS
ΔV =0.846 km/s
+ 0.050 km/s orbital maint.

Rendezvous & Circ by MPCV
(ΔV =0.035 km/s)

Dock All Elements
(crew transfer)

TEI MPCV
(ΔV = 0.907 km/s)

5 d Transit

TLI by Depot/CPS
(ΔV = 3.127 km/s)

4 d Transit

LEO 407 km x 407 km

Deliver Depot

Fill Depot

Fill CPS

TCM burns by MPCV
(ΔV = 0.010 km/s)

CPS

MPCV

Lander

Commercial Crew

MPCV SM

EDL

Note: spacecraft icons are not to scale

EARTH

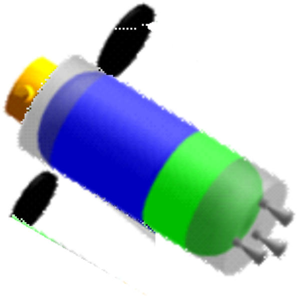
Earth

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Lunar Propellant LO2/LH2 Depot/CPS

DRM 33C Depot LOX/LH2



Propellants	**LOX/LH2**
Stage Diameter	**6 m**
Stage Length	**16 m**
Oxidizer Boiloff	**0%/month**
Fuel Boiloff	**0.5%/month**
Sub-orbital T/W	**0.72**
Orbital T/W	**0.15**
Power	**2625 W**
Cryocooler Power	**1625 W**
Mass Growth, %	**30**
# Engines / Type	**3 RL10 B-2**
Engine Isp (100%)	**464 sec**

	Mass, kg
2. Body Structure	5,213
3. Induced Environmental Protection	319
5. Main Propulsion	852
6. Orient Control Separation	140
7. Prime Power	137
8. Power Conversion and Distribution	27
9. Guidance and Navigation	38
10. Instrumention	32
11. Communication	97
12. Thermal Control	1,521
16. Range Safety and Abort	69
16a. Mass Growth Allowance	2,539
19. Ordanance	20
Dry Mass	**11,002**
21. Residual Propellant	2,115
23. Inflight Losses	14
25a. RCS Propellant	5,209
25. Total Propellant inc Boiloff	105,767
IMLEO	**179,813**

Propellant Burn 1	102,917
Payload Burn 1	55,706
DeltaV Burn 1	3,973

Description:

The combined propellant depot and CPS stage is capable of holding enough O2 and H2 (100MT) to perform Lunar missions requiring up to 4 km/s of delta-V when used as a CPS stage. Both the Depot and CPS have MLI (SOFI for ground hold and 60 layer MLI), cryocoolers, and sunshield. Power is with Ultraflex solar cells.

Both the Depot and Depot-Derived CPS can be launched from a Falcon Heavy or Delta IV Heavy replacing the second stage of the launch vehicle and using the RL 10 engines to place itself into a 407 km, 28.5 deg inclination circular orbit.

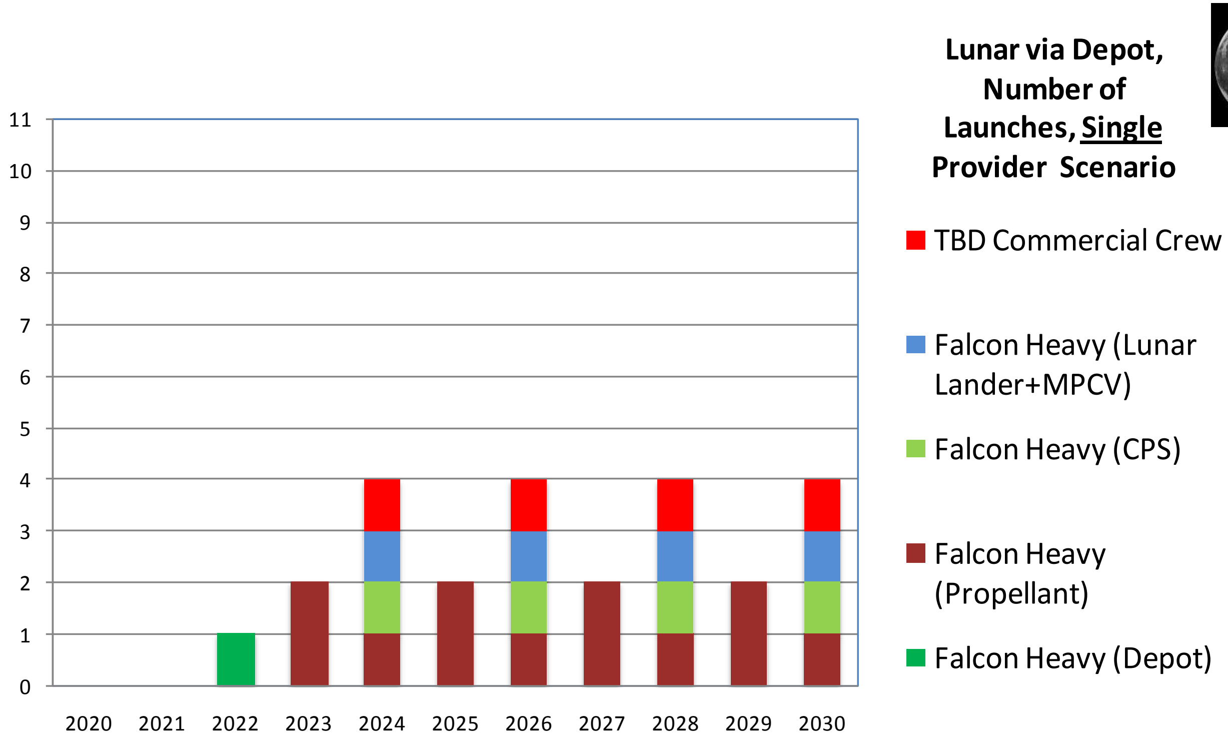
WWW.NASAWATCH.COM

Lunar Mission Falcon Heavy Launch Schedule

4 Lunar Missions / 24 Launches after Depot Placement

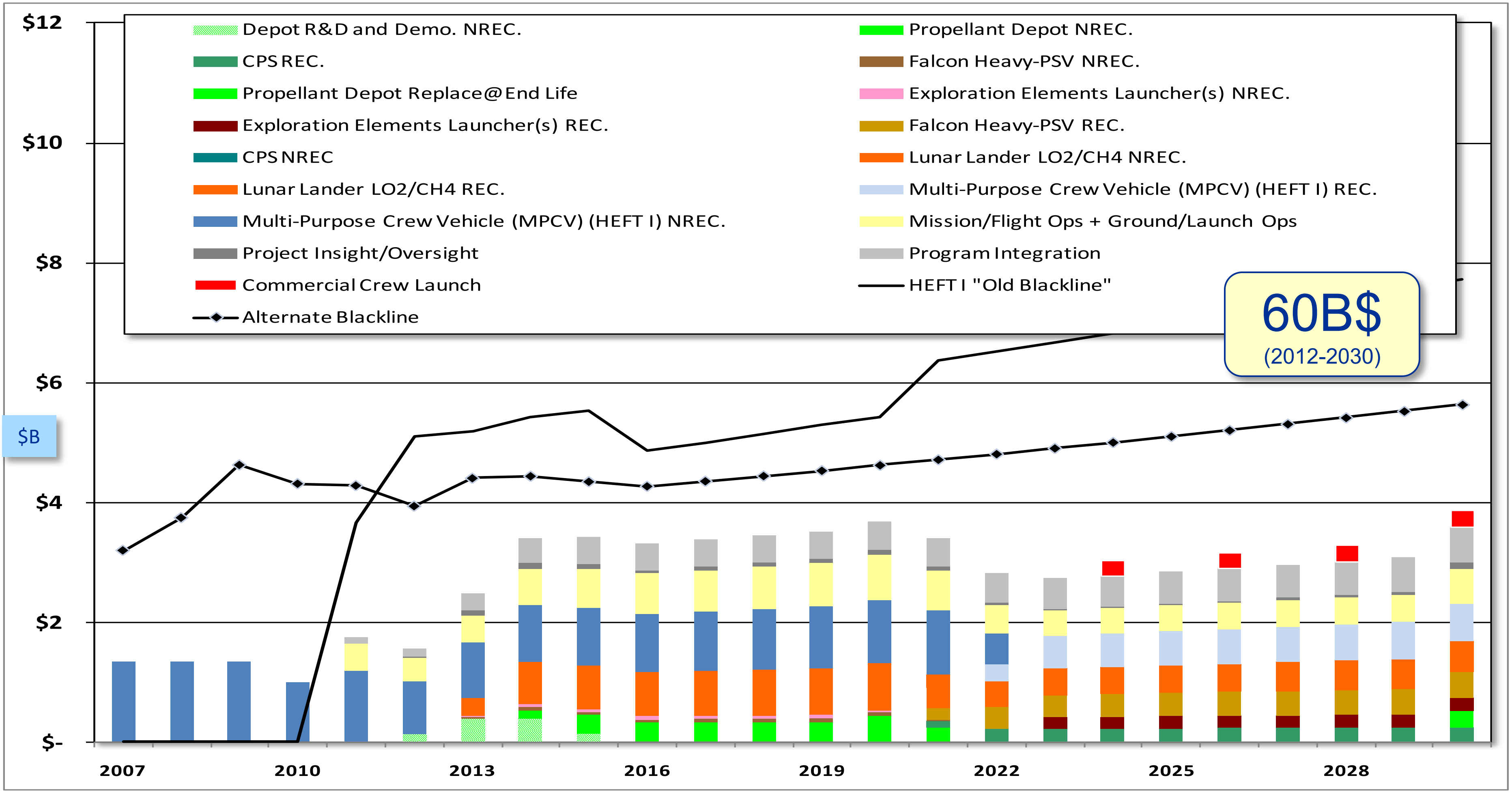
< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

Reserve propellant flights – not shown



WWW.NASAWATCH.COM

Falcon Heavy Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years



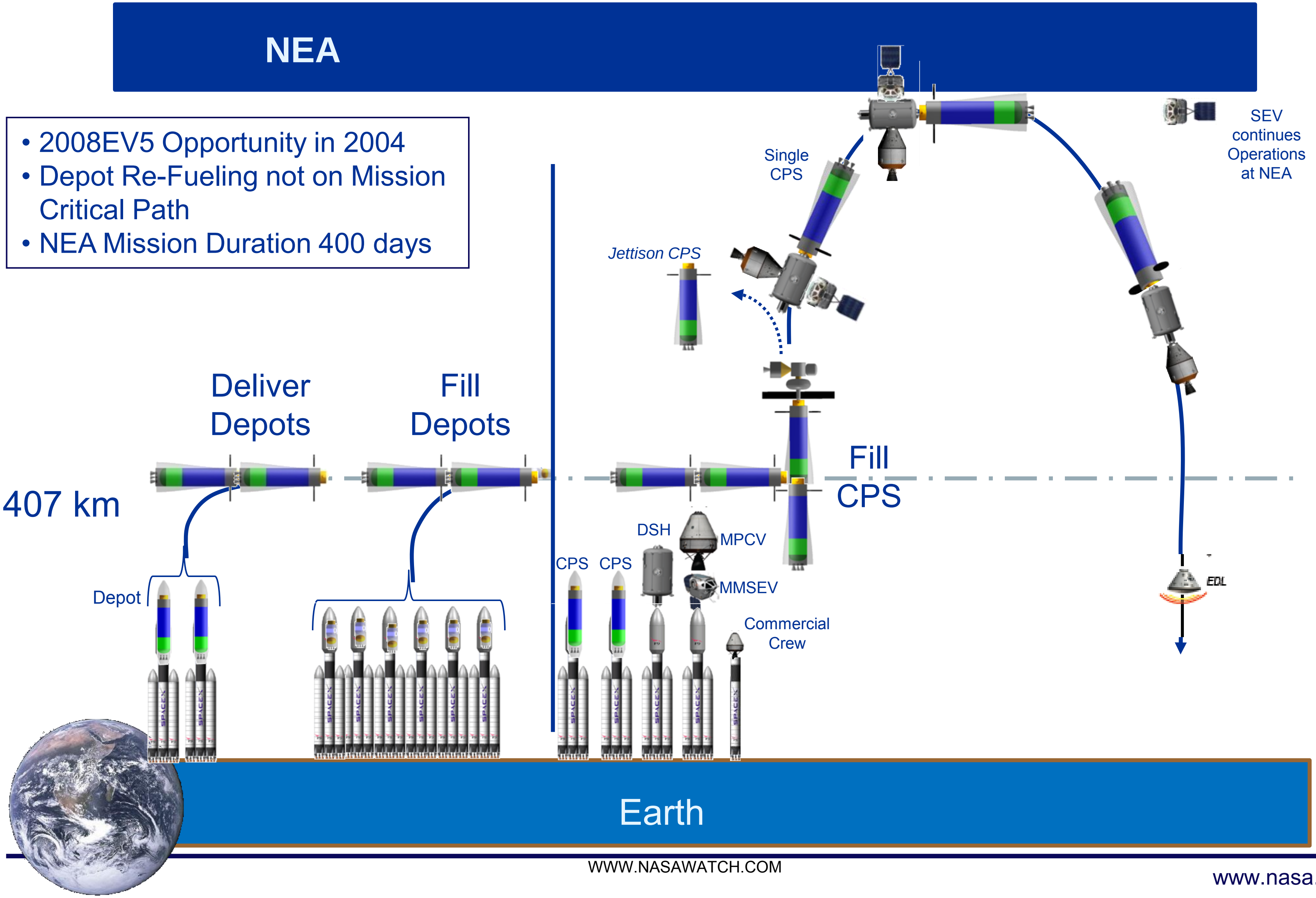
60B$
(2012-2030)

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 34B w/ 50MT Falcon Heavy + Two-Stage Lunar Propellant Depot/CPS

- 2008EV5 Opportunity in 2004
- Depot Re-Fueling not on Mission Critical Path
- NEA Mission Duration 400 days



WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Lunar Mission Observations – Falcon Heavy LV

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 4-8 lunar missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first lunar mission to in 2024, potentially several years earlier than HLLV-based approaches
- Launch capacity does not appear to be a major issue
- Use of lunar-derived CPS/depot for two-stage NEA missions adds ops cost/complexity but saves on DDT&E and size
- Dependence on a single CLV and provider likely unacceptable
- Integration of large CPS stage with small-diameter Falcon easier due to smaller stage size
- Integration of lunar lander on Falcon limits design options

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

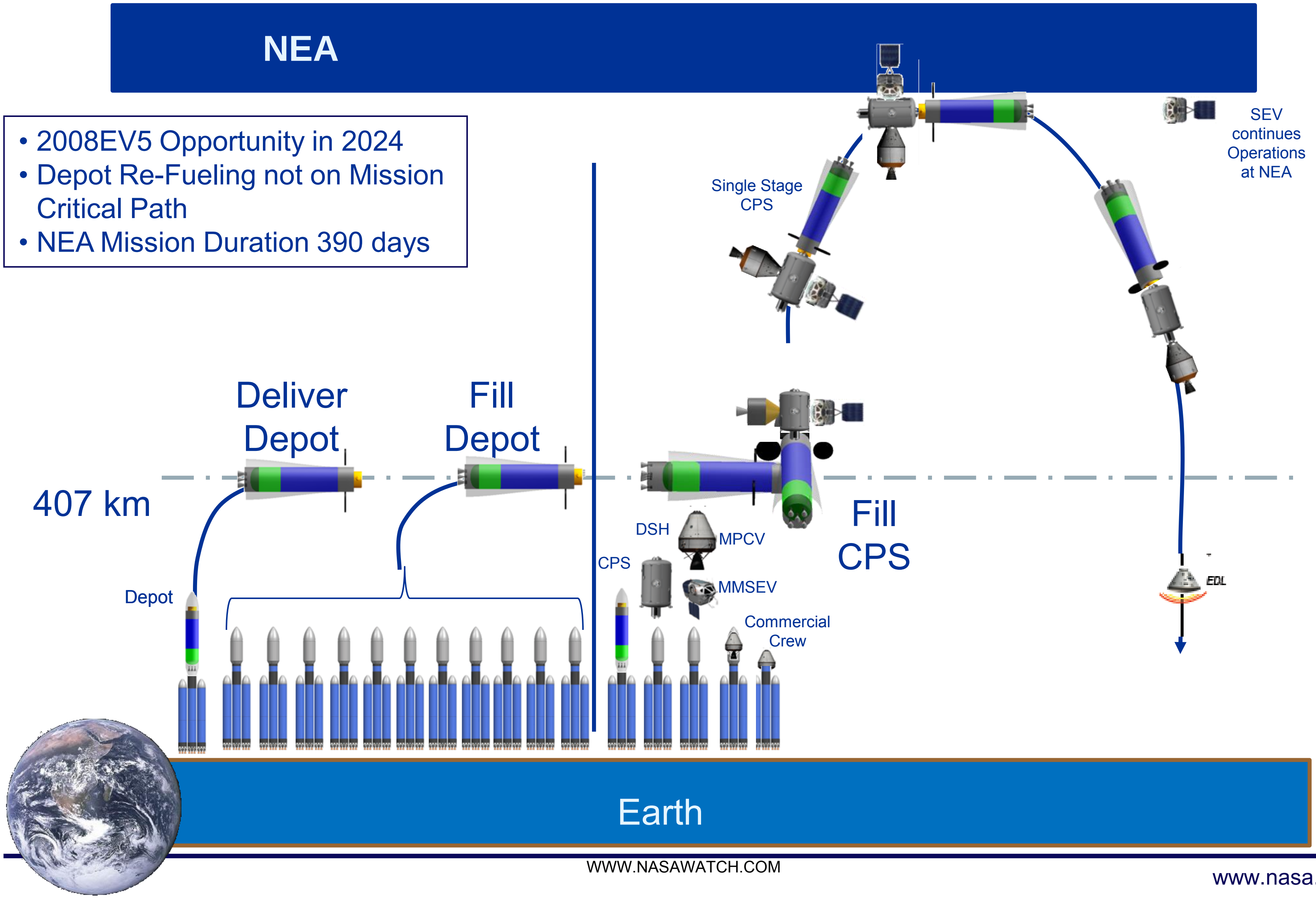
NEA Missions With Depot/CPS, With Delta IV Heavy LV

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 34B w/ 28MT Delta IV Heavy + Propellant Depot/CPS

- 2008EV5 Opportunity in 2024
- Depot Re-Fueling not on Mission Critical Path
- NEA Mission Duration 390 days



WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

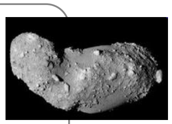
NEA Mission Delta IV Heavy Launch Schedule

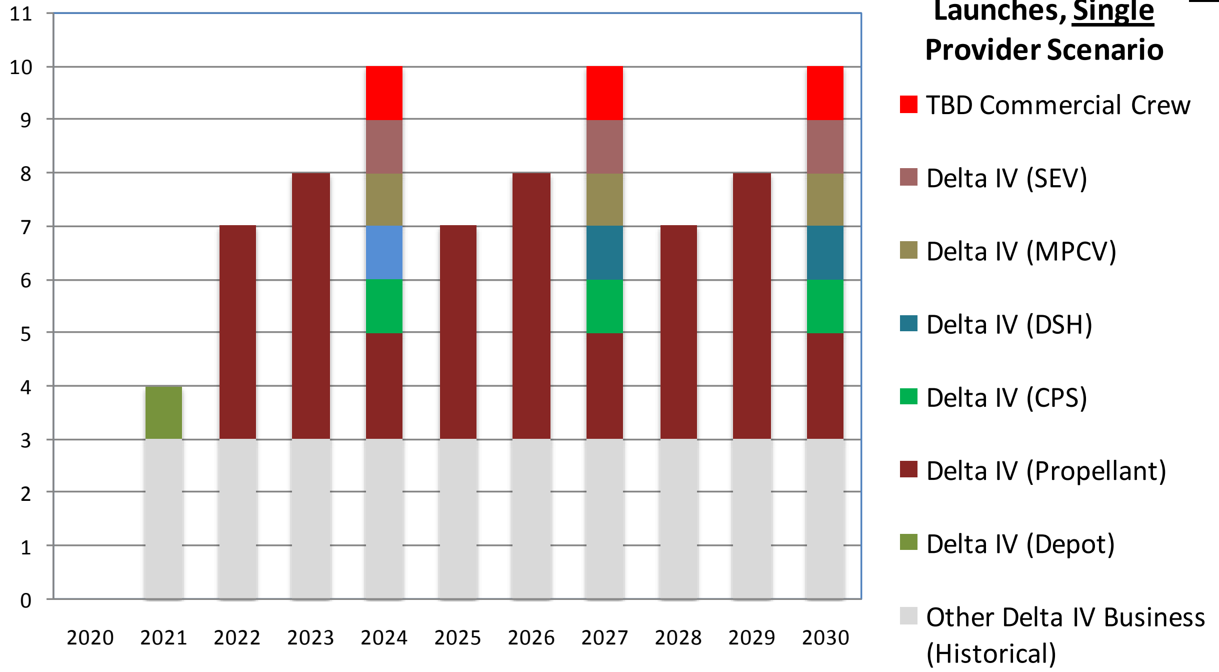
3 NEA Missions / 48 Launches after Depot Placement

< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

Reserve propellant flights – not shown

NEA via Depot, Number of Launches, Single Provider Scenario

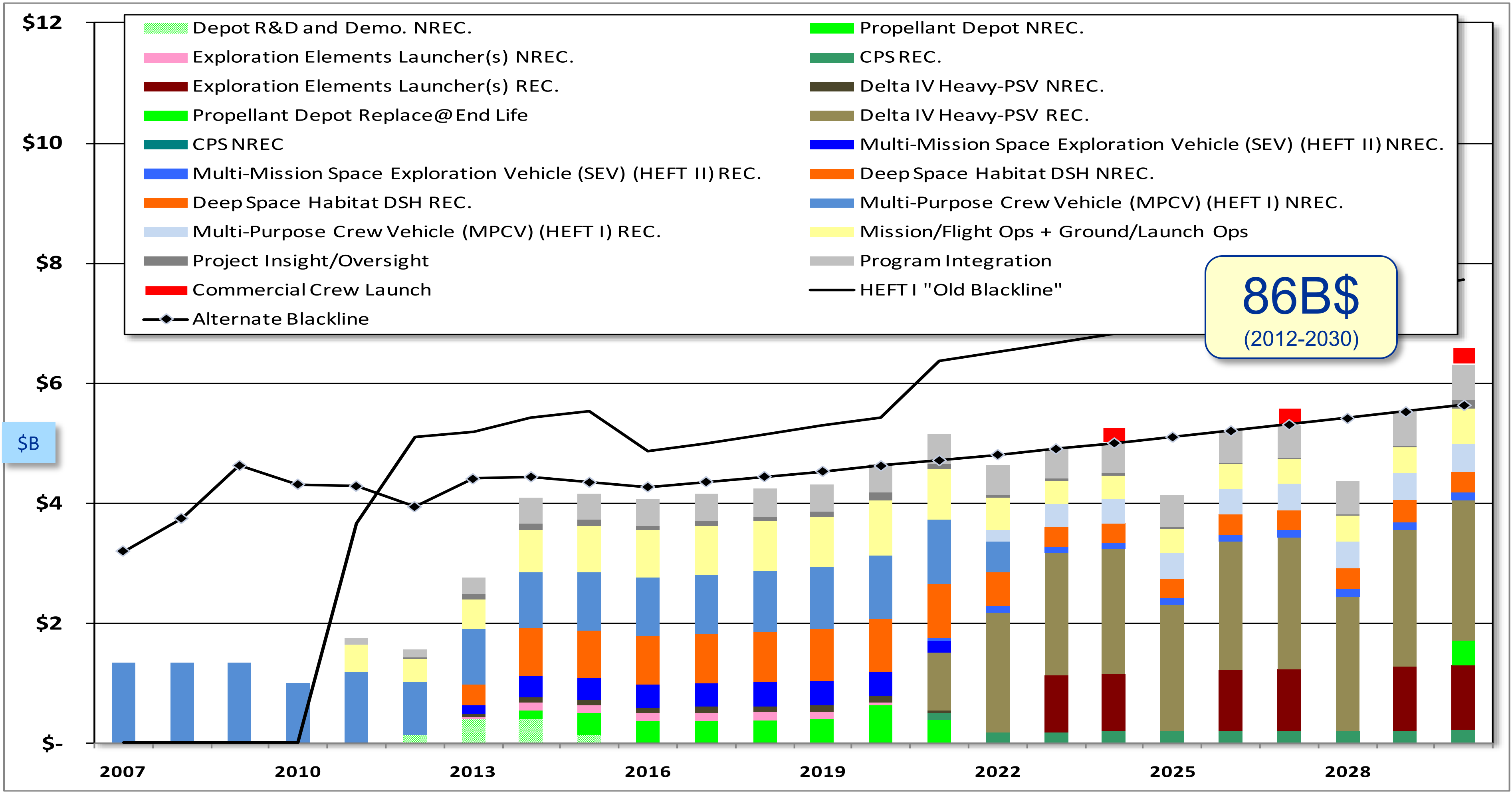




WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Delta IV Heavy Based NEA Mission LCC, First Mission 2024, Missions Every 3 Years



WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

NEA Mission Observations – Delta IV Heavy LV

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
    - $24B more than all Falcon Heavy approach
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 3 NEA missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first mission to NEA in 2024, potentially several years earlier than HLLV/SEP-based approaches, meeting President's deadline and actual availability of NEA 2008EV5
- Delta IV Heavy launch capacity could be an issue, significant non-recurring investments will be required
- Dependence on a single CLV and provider likely unacceptable
- Integration of large CPS stage with Delta IV adds some complexity, but not as much as with Falcon Heavy

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

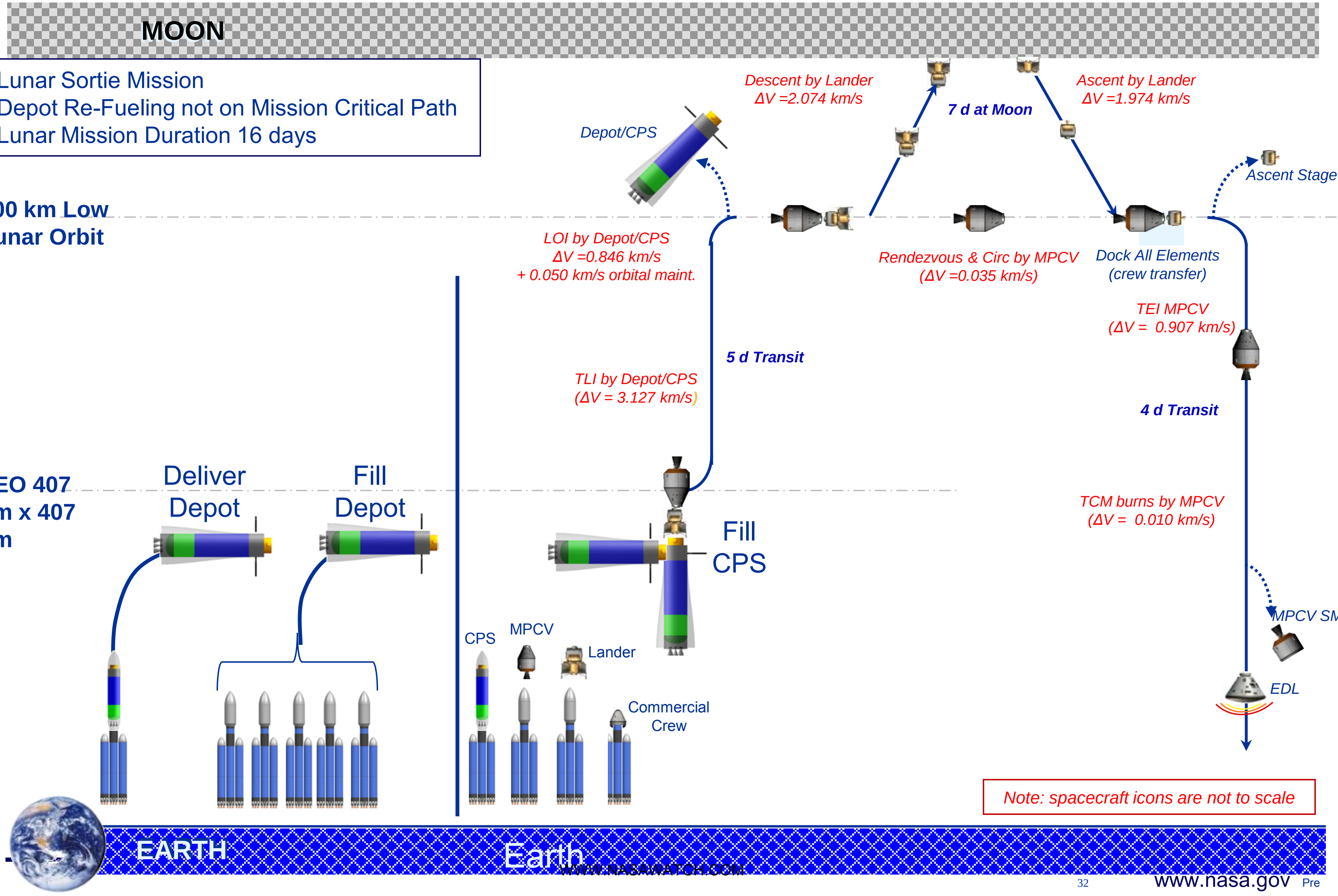
Lunar Missions With Depot/CPS, With Delta IV Heavy LV

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 33C w/ 28MT Delta IV Heavy + Propellant Depot/CPS

- Lunar Sortie Mission
- Depot Re-Fueling not on Mission Critical Path
- Lunar Mission Duration 16 days



MOON

100 km Low Lunar Orbit

LEO 407 km x 407 km

Deliver Depot

Fill Depot

CPS

MPCV

Lander

Commercial Crew

Fill CPS

TLI by Depot/CPS (ΔV = 3.127 km/s)

5 d Transit

LOI by Depot/CPS ΔV =0.846 km/s + 0.050 km/s orbital maint.

Depot/CPS

Descent by Lander ΔV =2.074 km/s

7 d at Moon

Ascent by Lander ΔV =1.974 km/s

Rendezvous & Circ by MPCV (ΔV =0.035 km/s)

Dock All Elements (crew transfer)

Ascent Stage

TEI MPCV (ΔV = 0.907 km/s)

4 d Transit

TCM burns by MPCV (ΔV = 0.010 km/s)

MPCV SM

EDL

Note: spacecraft icons are not to scale

EARTH

Earth

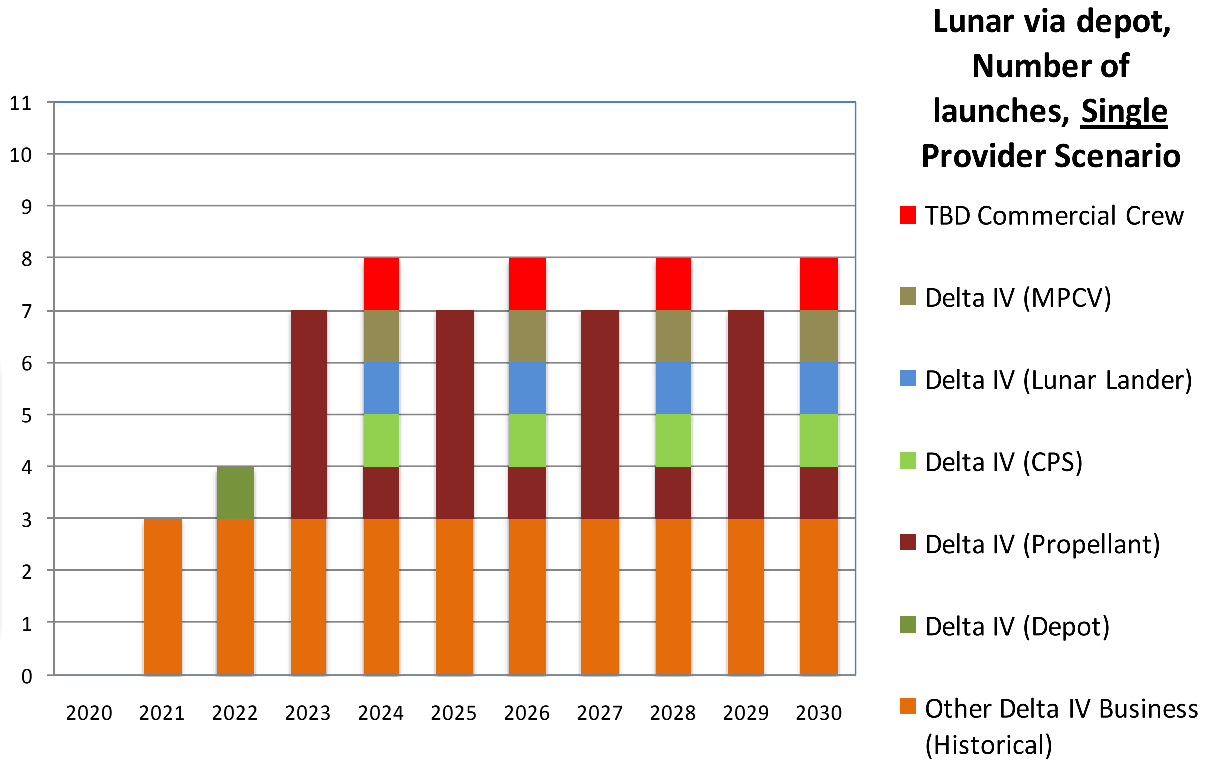
WWW.NASAWATCH.COM

Lunar Mission Delta IV Heavy Launch Schedule

4 Lunar Missions / 36 Launches after Depot Placement

< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

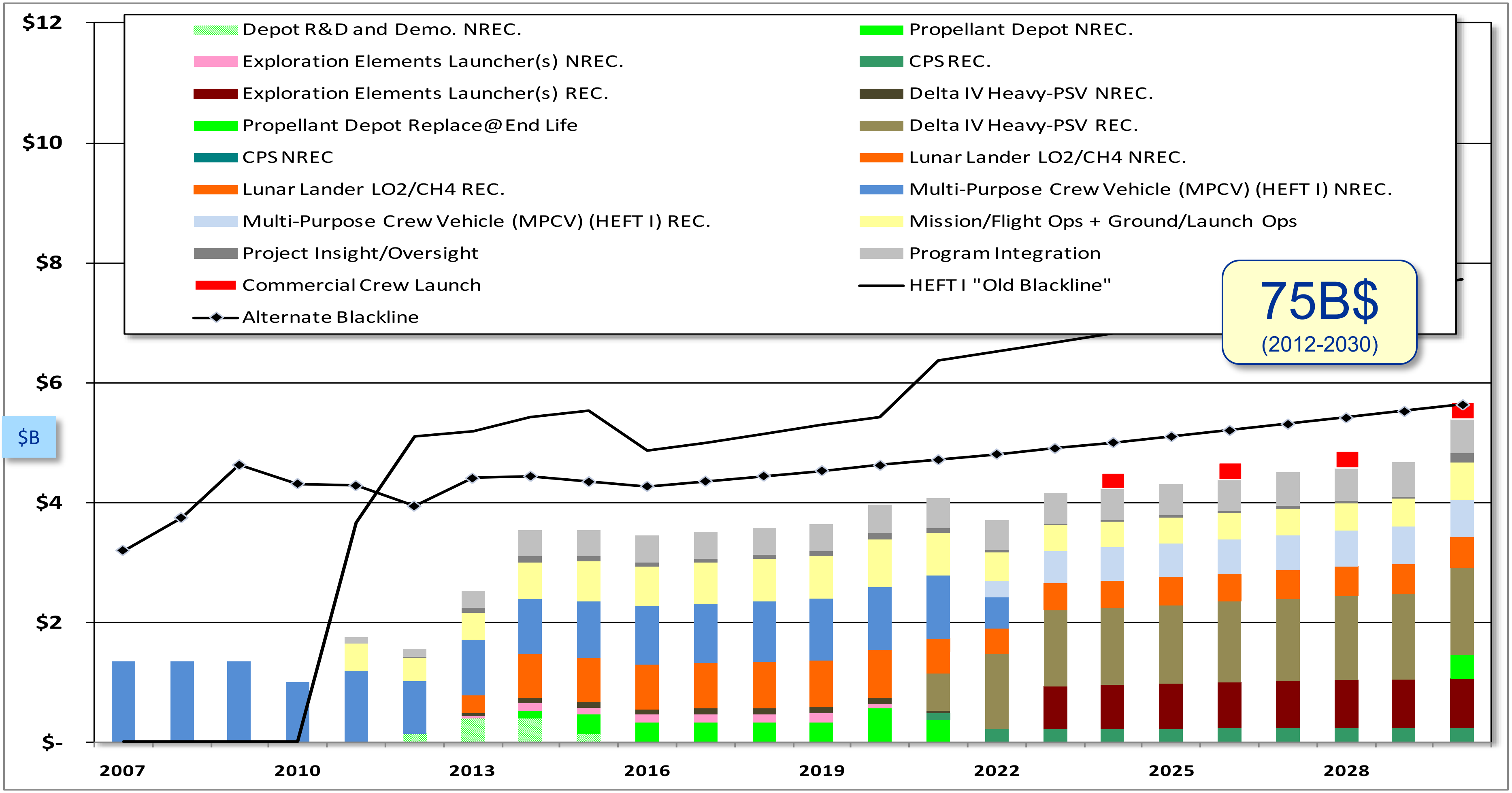
Reserve propellant flights – not shown



Lunar via depot, Number of launches, Single Provider Scenario

WWW.NASAWATCH.COM

Delta IV Heavy Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years



75B$
(2012-2030)

WWW.NASAWATCH.COM

Lunar Mission Observations – Delta IV Heavy LV

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
  - -$15B more than all Falcon Heavy approach
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 4-6 lunar missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first lunar mission to in 2024, potentially several years earlier than HLLV-based approaches
- Delta IV Heavy launch capacity could be an issue, significant non-recurring investments will be required
- Use of lunar-derived CPS/depot for two-stage NEA missions adds ops cost/complexity but saves on DDT&E and size
- Dependence on a single CLV and provider likely unacceptable
- Integration of smaller CPS stage with Delta IV Heavy easier
- Integration of lunar lander on Delta IV Heavy easier

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

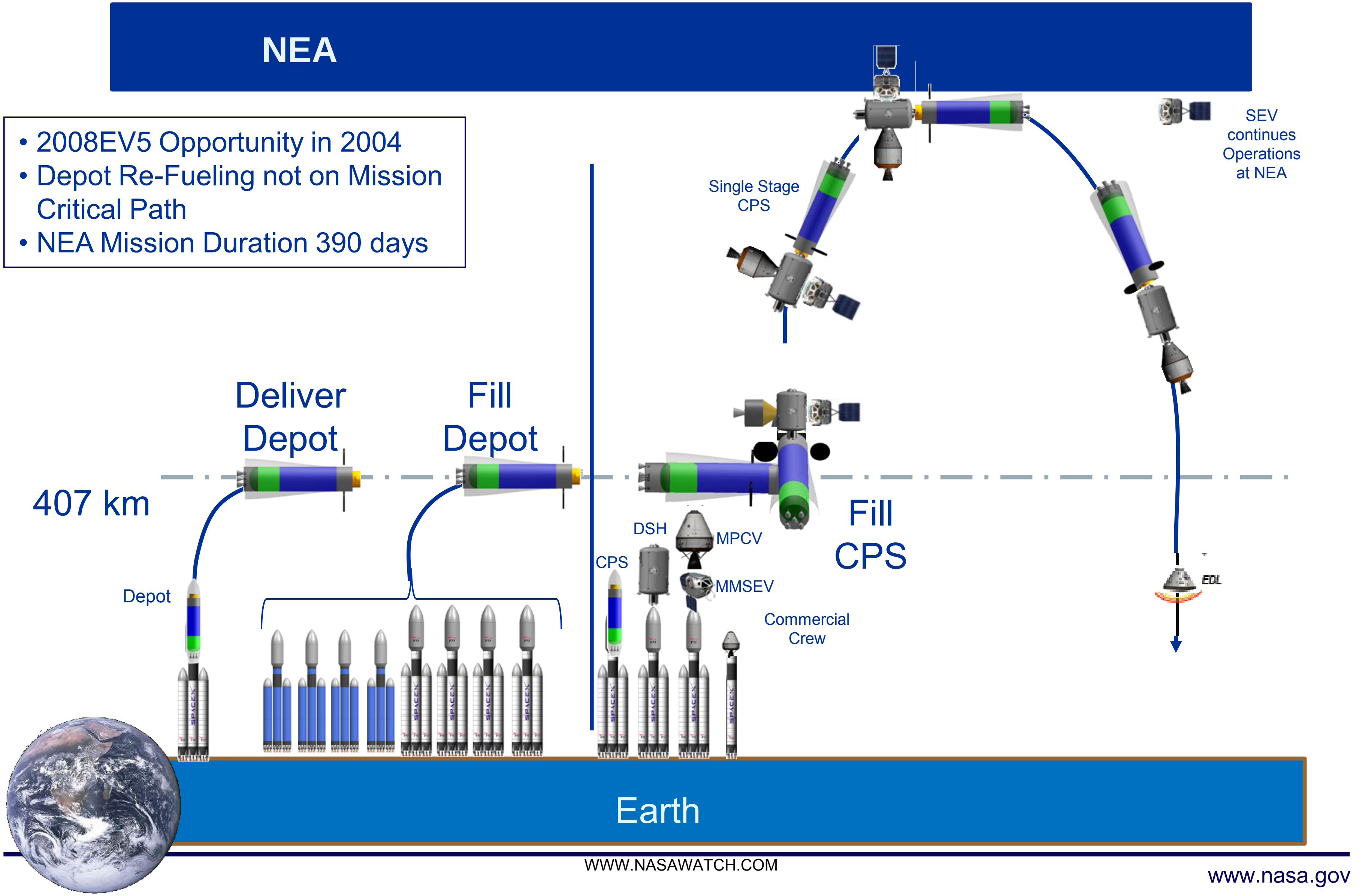
NEA Missions With Depot/CPS, With Mixed Fleet of Falcon Heavy and Delta IV Heavy LVs

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 34B w/ Mixed Fleet + Propellant Depot/CPS

- 2008EV5 Opportunity in 2004
- Depot Re-Fueling not on Mission Critical Path
- NEA Mission Duration 390 days



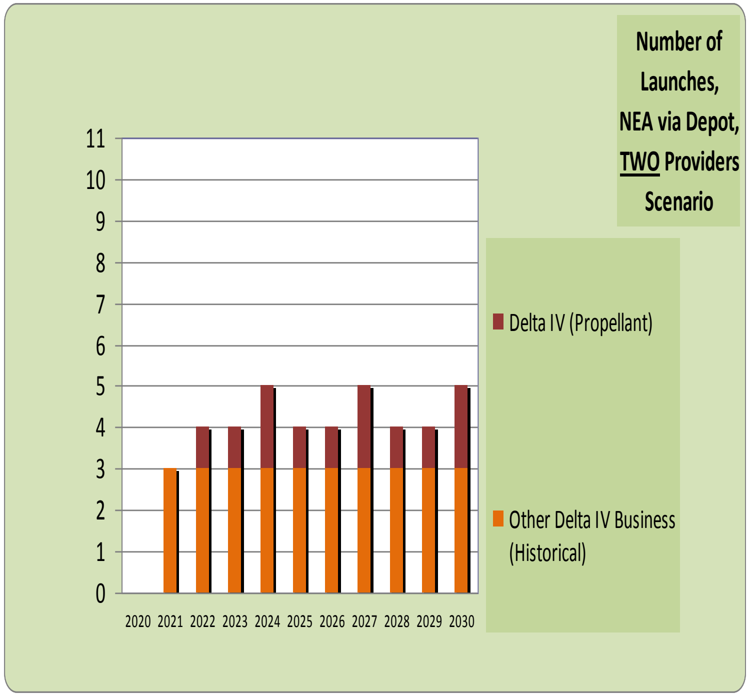
WWW.NASAWATCH.COM

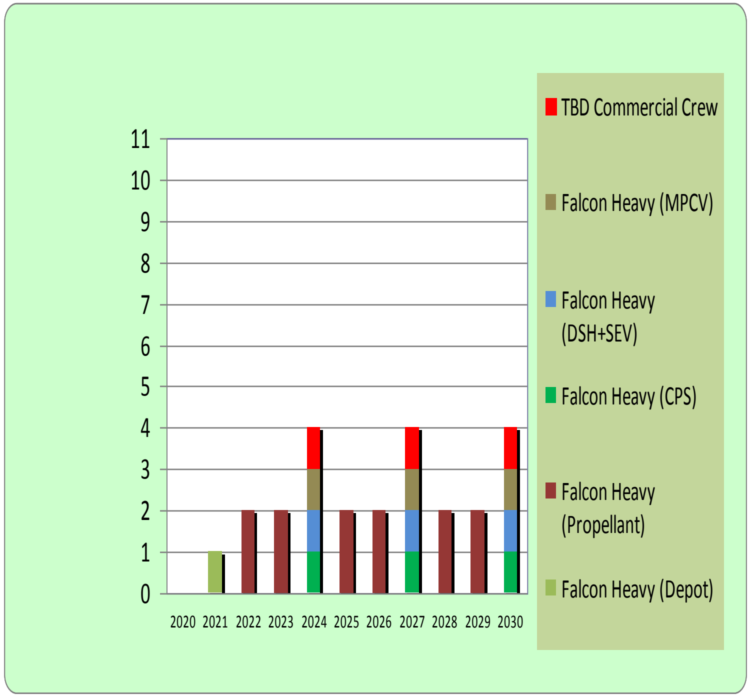
NEA Mission Delta IV & Falcon Heavy Mixed Fleet / Dual-Providers Launch Schedule

- NEA Mixed Fleet: This two-provider scenario could mitigate many of the issues that arise with NEA single provider scenarios.
- Delta IV w. shifts/staff & improvements gets to ~ 5 LPY with existing launch pad.
    - Costing, to be conservative, includes an extra launch pad cost.

Mixed Fleet Architecture – Separate infrastructure, supporting the same exploration missions

Note!
Other combinations possible.

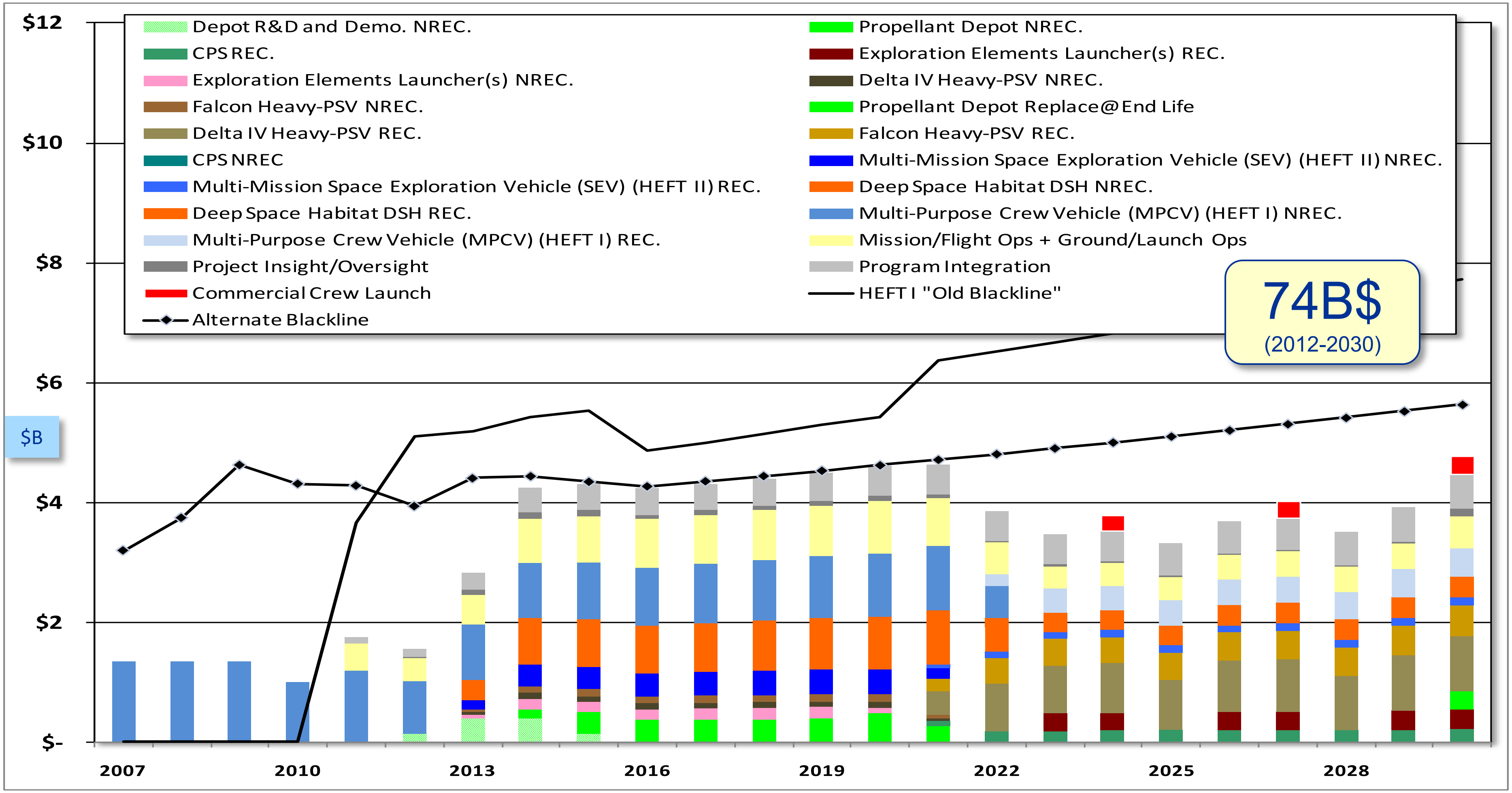




3 NEA Missions / 36 Launches after Depot Placement

WWW.NASAWATCH.COM

Delta IV & Falcon Heavy Mixed Fleet Based NEA Mission LCC, First Mission 2024, Missions Every 3 Years



74B$
(2012-2030)

WWW.NASAWATCH.COM

NEA Mission Observations – Mixed Fleet

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
  - Only $10B more than all Falcon Heavy approach
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 3-4 NEA missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first mission to NEA in 2024, potentially several years earlier than HLLV/SEP-based approaches, meeting President’s deadline and actual availability of NEA 2008EV5
- Launch capacity not much of an issue with two suppliers
  - Availability risk also improved
- Use of two CLVs, similar to COTS, should reduce cost and risk through competition
- Integration of large CPS stage with multiple vehicles could reduce commonality and add complexity

WWW.NASAWATCH.COM

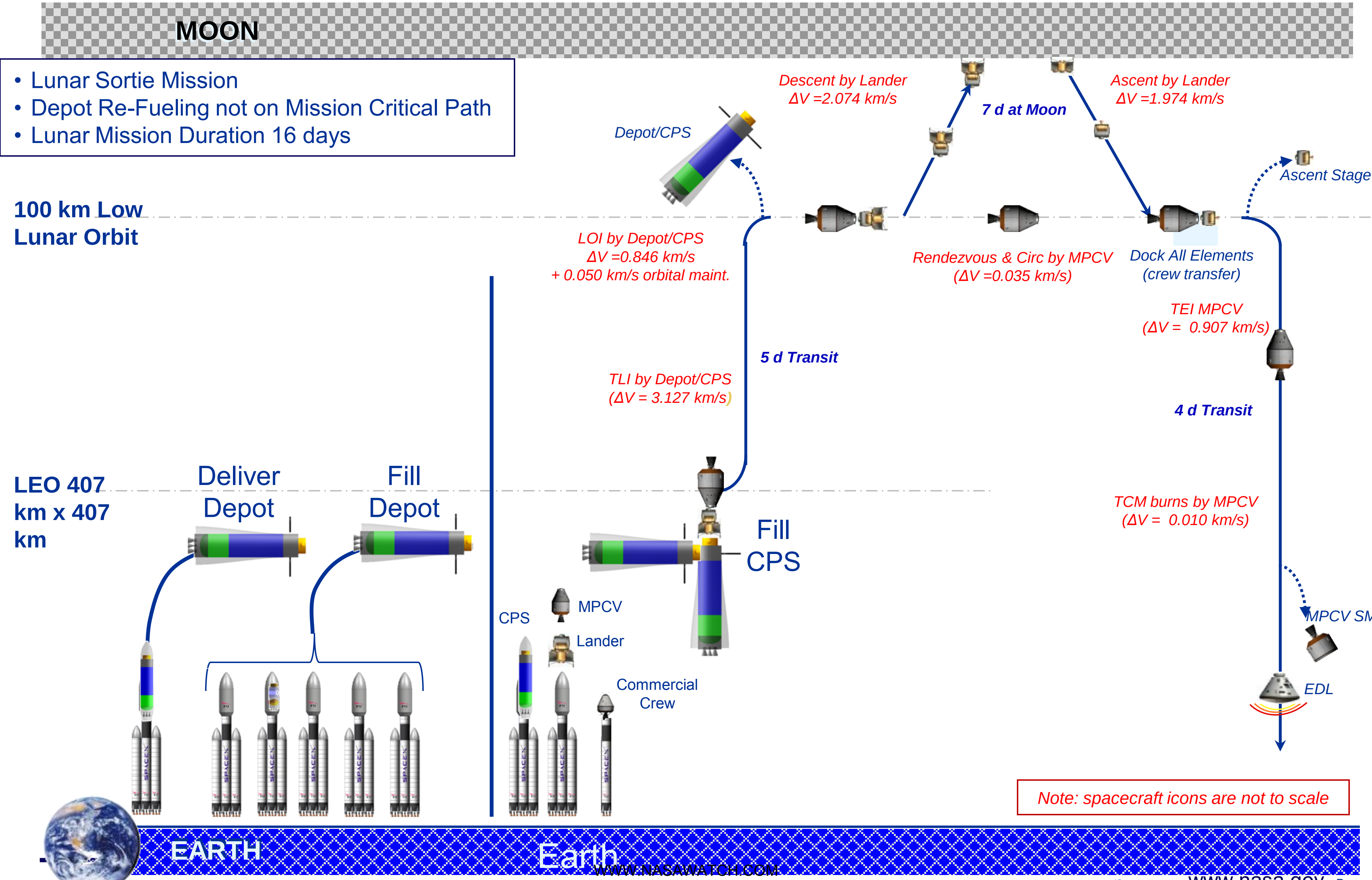
LO2/RP Depot/CPS Analysis Results

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

DRM 33C w/ 50MT Falcon Heavy + Propellant RP Depot/CPS

- Lunar Sortie Mission
- Depot Re-Fueling not on Mission Critical Path
- Lunar Mission Duration 16 days



MOON

100 km Low Lunar Orbit

LEO 407 km x 407 km

EARTH

Earth

Deliver Depot

Fill Depot

CPS

MPCV

Lander

Commercial Crew

Fill CPS

TLI by Depot/CPS (ΔV = 3.127 km/s)

5 d Transit

LOI by Depot/CPS ΔV =0.846 km/s + 0.050 km/s orbital maint.

Depot/CPS

Descent by Lander ΔV =2.074 km/s

7 d at Moon

Ascent by Lander ΔV =1.974 km/s

Rendezvous & Circ by MPCV (ΔV =0.035 km/s)

Dock All Elements (crew transfer)

Ascent Stage

TEI MPCV (ΔV = 0.907 km/s)

4 d Transit

TCM burns by MPCV (ΔV = 0.010 km/s)

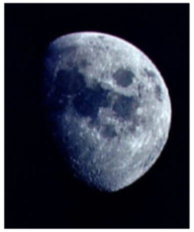
MPCV SM

EDL

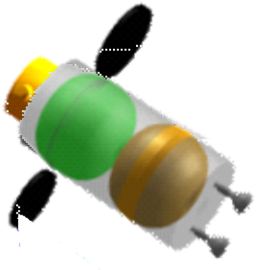
Note: spacecraft icons are not to scale

WWW.NASAWATCH.COM

Lunar Propellant LO2/RP Depot/CPS



DRM33C LOX/RP



Propellants	**LOX/RP-1**
Stage Diameter	**6 m**
Stage Length	**11 m**
Oxidizer Boiloff	**0%/month**
Fuel Boiloff	**0%/month**
Sub-orbital T/W	**0.72**
Orbital T/W	**0.17**
Power	**4152 W**
Cryocooler Power	**2152 W**
Mass Growth, %	**30**
# Engines / Type	**2 Merlins**
Engine Isp (100%)	**342 sec**

	Mass, kg
2. Body Structure	4,427
3. Induced Environmental Protection	247
5. Main Propulsion	1,464
6. Orient Control Separation	147
7. Prime Power	349
8. Power Conversion and Distribution	70
9. Guidance and Navigation	38
10. Instrumention	32
11. Communication	97
12. Thermal Control	1,417
16. Range Safety and Abort	69
16a. Mass Growth Allowance	2,513
19. Ordanance	20
Dry Mass	**10,890**
21. Residual Propellant	3,419
23. Inflight Losses	22
25a. RCS Propellant	5,300
25. Total Propellant inc Boiloff	170,968
IMLEO	**246,305**

Propellant Burn 1	170,968
Payload Burn 1	55,706
DeltaV Burn 1	3,973

Description:

The combined propellant depot and CPS stage is capable of holding enough O2 and RP (170MT) to perform Lunar missions requiring up to 4 km/s of delta-V when used as a CPS stage. Both the Depot and CPS have MLI (SOFI for ground hold and 60 layer MLI), cryocoolers, and sunshield. Power is with Ultraflex solar cells.

Both the Depot and Depot-Derived CPS can be launched from a Falcon Heavy or Delta IV Heavy replacing the second stage of the launch vehicle and using the Merlin engines to place itself into a 407 km, 28.5 deg inclination circular orbit.

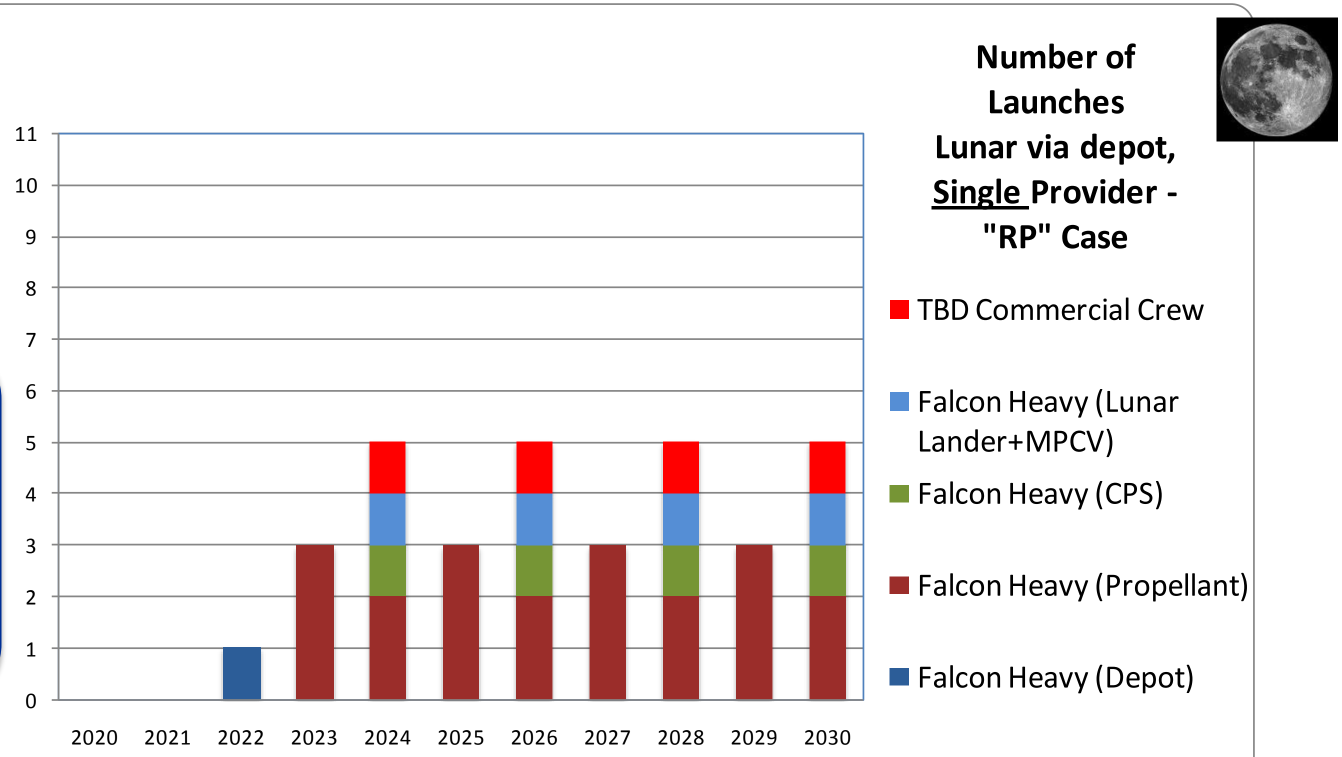
WWW.NASAWATCH.COM

RP Lunar Mission Falcon Heavy Launch Schedule

4 Lunar Missions / 28 Launches after Depot Placement

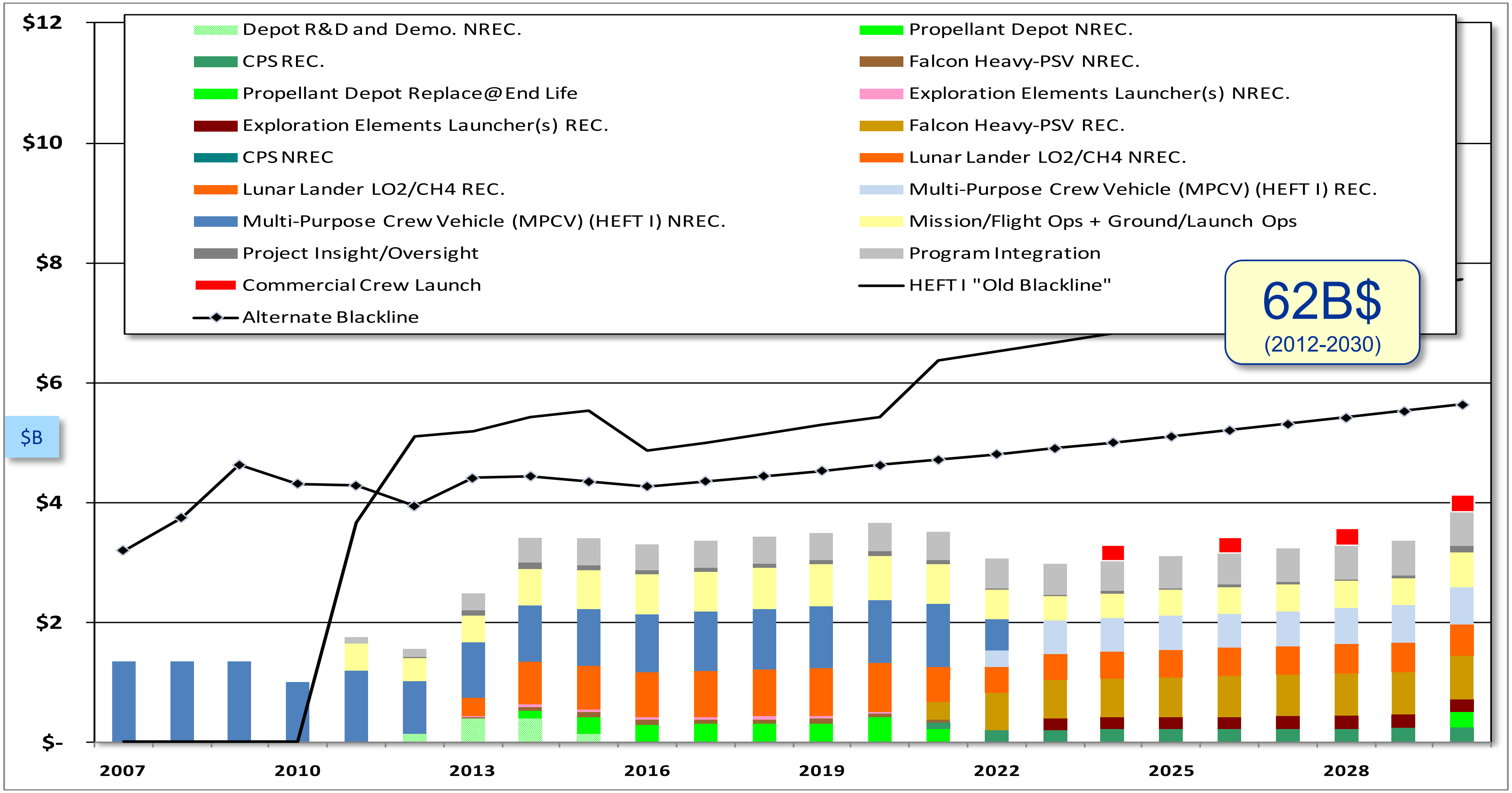
< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

Reserve propellant flights – not shown



WWW.NASAWATCH.COM

Falcon Heavy RP Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years



62B$
(2012-2030)

WWW.NASAWATCH.COM

Lunar Mission Observations – RP Depot/CPS

- Costs $10s of billions less through 2030 over alternate HLLV/SEP-based architecture approaches
  - Only $2B more than LO2/LH2 Depot approach
- Fits within conservative exploration budget through 2030 with extended ISS and budget cuts while allowing 4-8 lunar missions
- Breaking costs into smaller, less-monolithic amounts allows great flexibility in meeting smaller and changing budget profiles
- Allows first lunar mission to in 2024, potentially several years earlier than HLLV-based approaches
- Launch capacity does not appear to be a major issue
- Dependence on a single CLV and provider likely unacceptable
- Integration of large CPS stage with small-diameter Falcon easier due to smaller stage size
- Integration of lunar lander on Falcon limits design options
- RP-based depot/CPS provides slightly higher LCC for lunar missions with lower risk

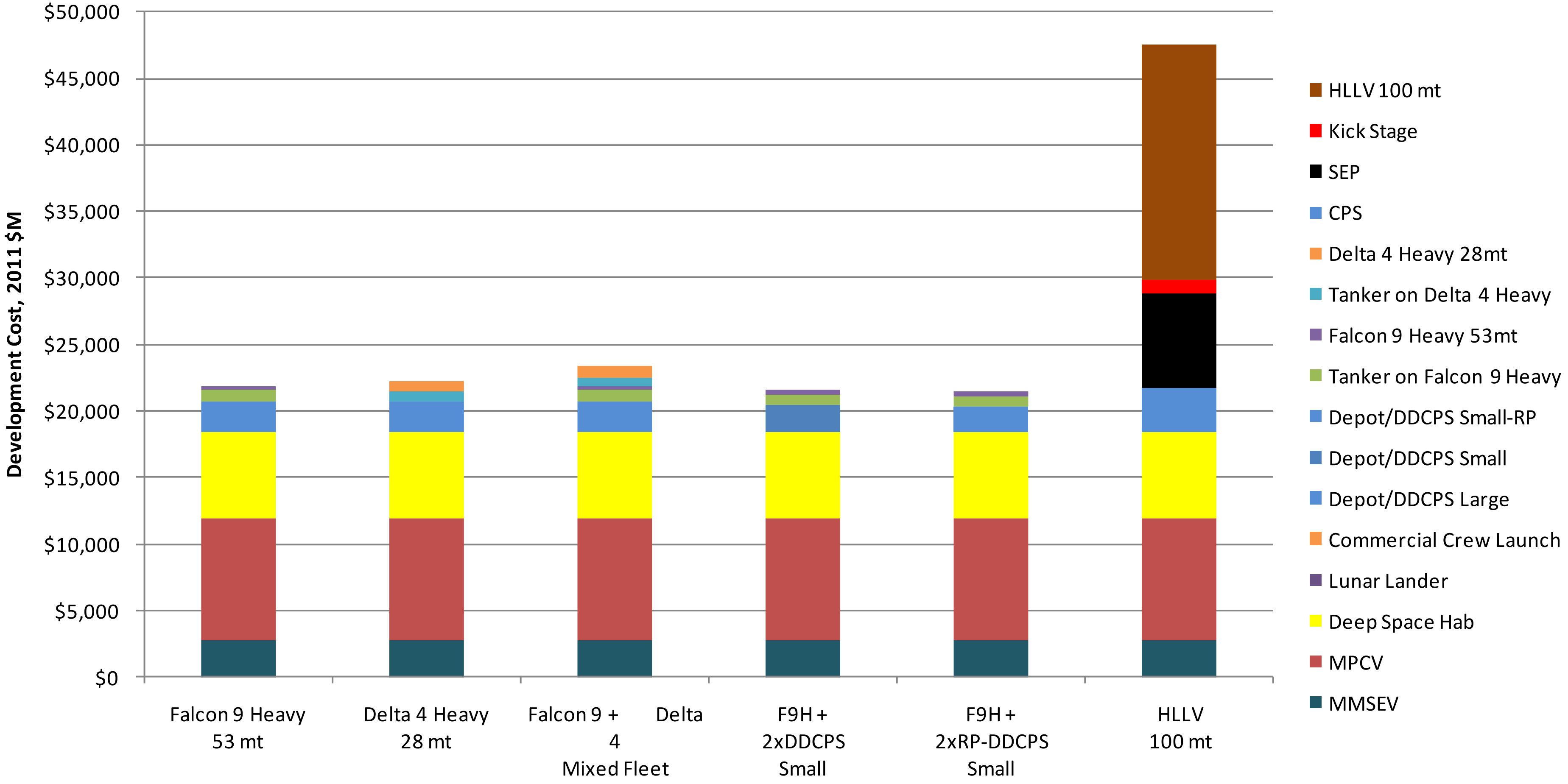
WWW.NASAWATCH.COM

Integrated Launch Vehicle/Costs Sensitivity Results

WWW.NASAWATCH.COM

NEA Mission (34B) Relative DDT&E Costs

Excluding Ground/Mission Ops and Oversight/Integration Costs

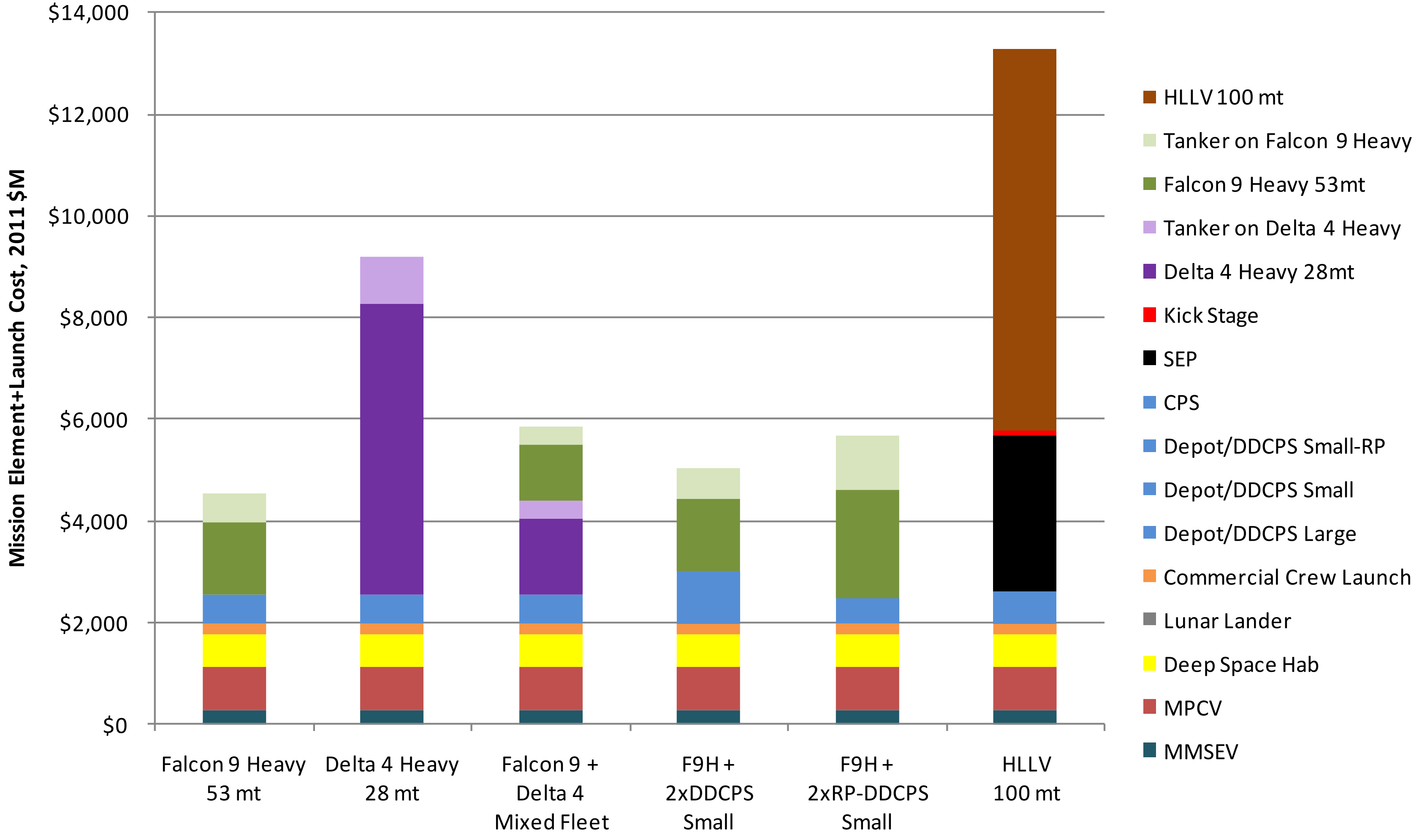


WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

NEA Mission (34B) Relative Mission Costs

Excluding Ground/Mission Ops and Oversight/Integration Costs

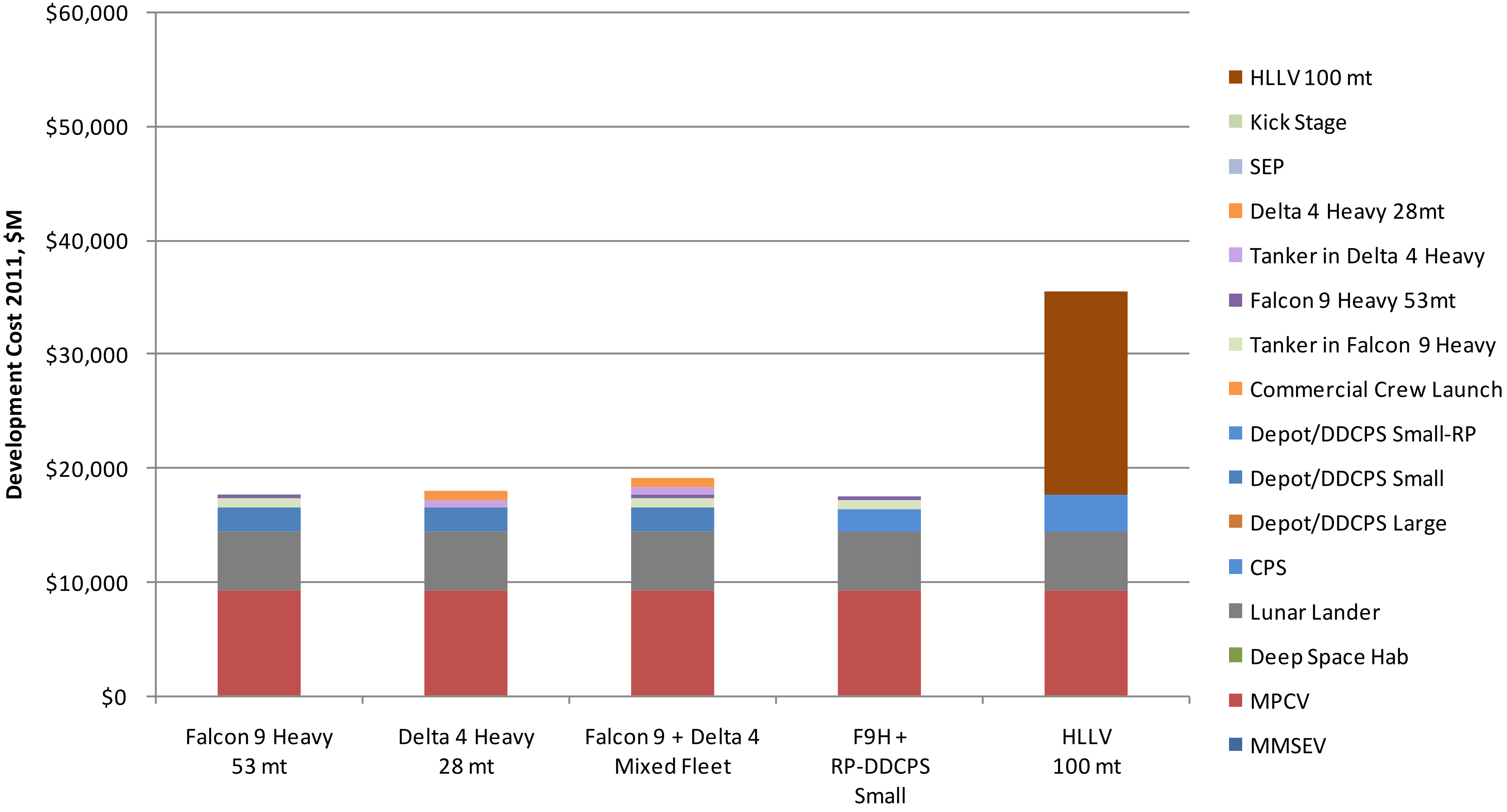


WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Lunar Mission (33C) Relative DDT&E Costs

Excluding Ground/Mission Ops and Oversight/Integration Costs

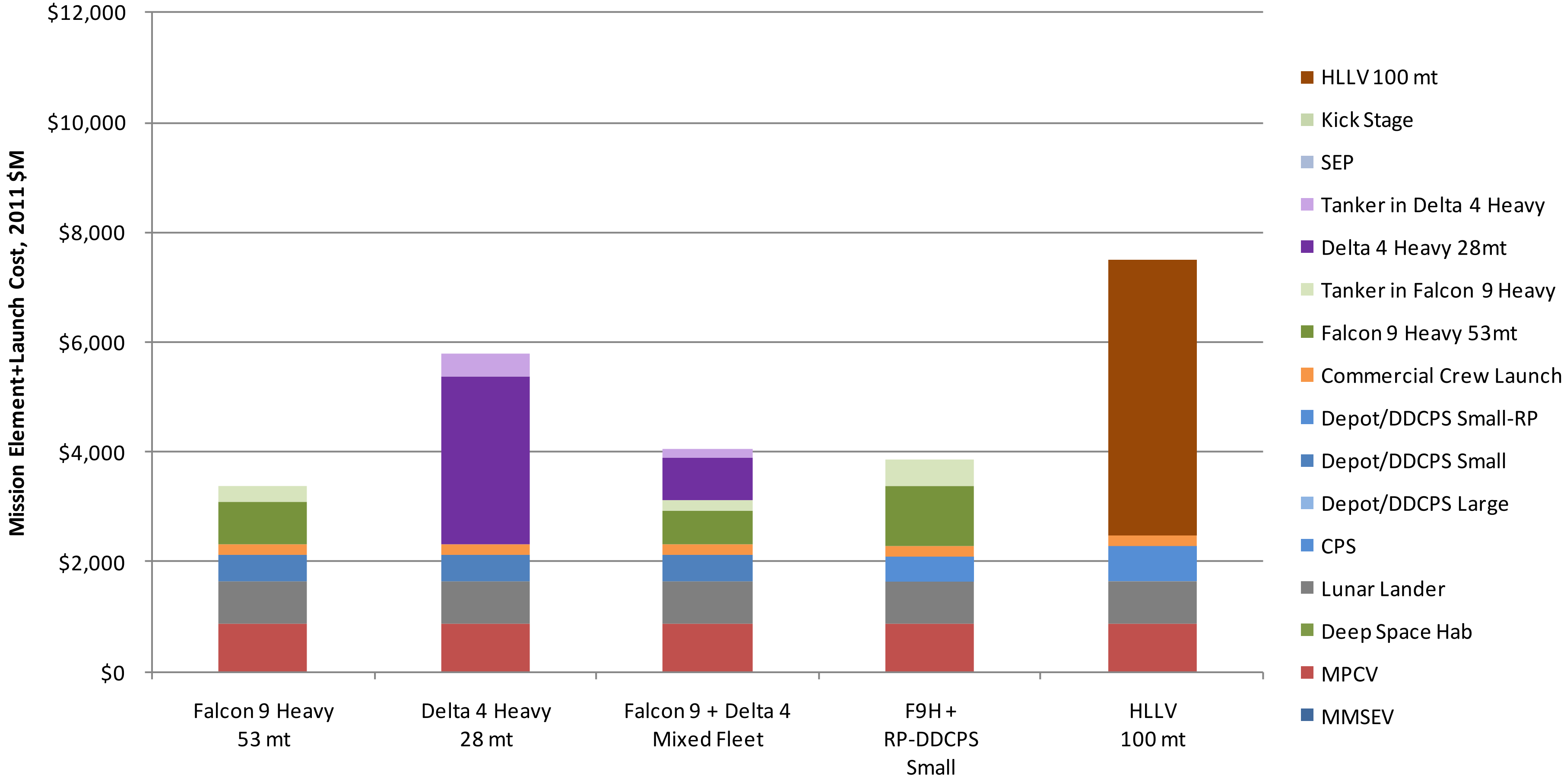


WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Lunar Mission (33C) Relative Mission Costs

Excluding Ground/Mission Ops and Oversight/Integration Costs



WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Mission Risk and Availability Analysis

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Risk and Reliability Analyses

Propellant Delivery Reliability with Contingency Missions

- Probability depot can be supplied using “n out of m” mission opportunities
- Drives number of contingency flights needed to assure some required level of reliability
- Use with Launch Availability and Depot Vehicle Reliability to estimate propellant delivery phase risk

Depot Vehicle Reliability and Risk Analysis

- Probability of loss of the depot over various time intervals
- Requested to help define planned life or time between servicing missions
- Identifies areas to consider for trades between increased redundancy and vehicle mass
- Evaluate effectiveness of increased MMOD shielding vs. mass
- Supports Mission Risk models for initial depot delivery, propellant delivery and “fill-up”, and propellant transfer to CPS phases

Launch Availability Analysis

- Probability that various planned launch sequences occur on time
- Needed to establish campaign start date to achieve a desired probability
- Drives depot on-orbit operational time requirement
- Needed to confirm adequacy of depot reliability / redundancy solution
- Defines boil-off allowances needed and confirm adequate margins with planned and contingency number of flights
- Establishes LEO loiter duration requirements for mission elements (CPS, DSH, MMSEV, MPCV)

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Risk and Reliability Analyses (cont.)

Exploration Loss of Mission - Operational (LOM_O) = LOM - LOC

- Risk Team requested to focus on LOM without LOC
- Probability of mission loss once depot is fully filled and ready for DRM to start
- 1st element launch through landing/recovery
- All exploration elements from launch through end of service
- Depot reliability from 1st element launch through propellant transfer to CPS and undock

Loss of Mission - Operational (LOM_O) for fill phase through first element launch

- Propellant launch/orbit insertion failure; non-catastrophic failure of AR&D or prop transfer
  - No loss of mission if failures are within planned contingency mission capability
- However, catastrophic fraction of AR&D or propellant transfer failures is LOM
- Depot systems failure or MMOD during this phase assumed to be LOM
- Partially covered in Launch Availability, but full integration with PRA not currently planned

Depot Loss of Mission - Operational (LOM_O) after exploration mission departure

- Probability of depot being available to support a follow-on DRM
- Should include depot systems failure, MMOD, and any planned maintenance
- Not currently being assessed due to limited resources

Integrate results and compare with non-depot missions

- Risk ranking, identify areas for optimization, and develop conclusions

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Analysis Status and Results

Propellant Delivery Reliability with Contingency Missions – Completed

- Initial assessment bounding a range of likely vehicles and number of missions is complete
- Can achieve very adequate reliability with a minimal number of contingency flights
- Multiple providers necessary to protect against long delay due to accident

Depot Vehicle Reliability and Risk Analysis - ECD 7/29

- Preliminary results completed 7/6 and reviewed with Depot Team
- Current top drivers: solar arrays, cryocoolers, thermodynamic vent system (TVS)
- Depot MMOD mass vs. risk data received from JSC/KX at COB on 7/15

Launch Availability Analysis - ECD 7/29

- Preliminary results for single/multiple LV providers complete 7/15 and reviewed with Depot Team
- Multiple providers and long time between missions contribute to high availability

Exploration Loss of Mission - Operational (LOM_O) - ECD 8/1/11

- Initial model run completed 07/15, initial results are not ready for release at this time, need to iterate and finalize results with Depot Team during the next two weeks prior to delivery of final results..
- Comparison of Propellant Depot 34B DRM LOM_O results to the December 2010 HEFT II 34B DRM LOM_O will follow delivery of final results. No updates have been made to the HEFT II 34B DRM PRA for this risk comparison. Additional time may be needed to reconcile changes since 12/2010.

Integrate results and compare with non-depot missions – ECD 8/17/11

- Revisit March 2011 notional qualitative assessment which considered potential benefit of depot in mitigating HEFT II 34B DRM PRA with other effects included (e.g., maintenance, additional redundancy, MMOD shielding, additional margins)

WWW.NASAWATCH.COM

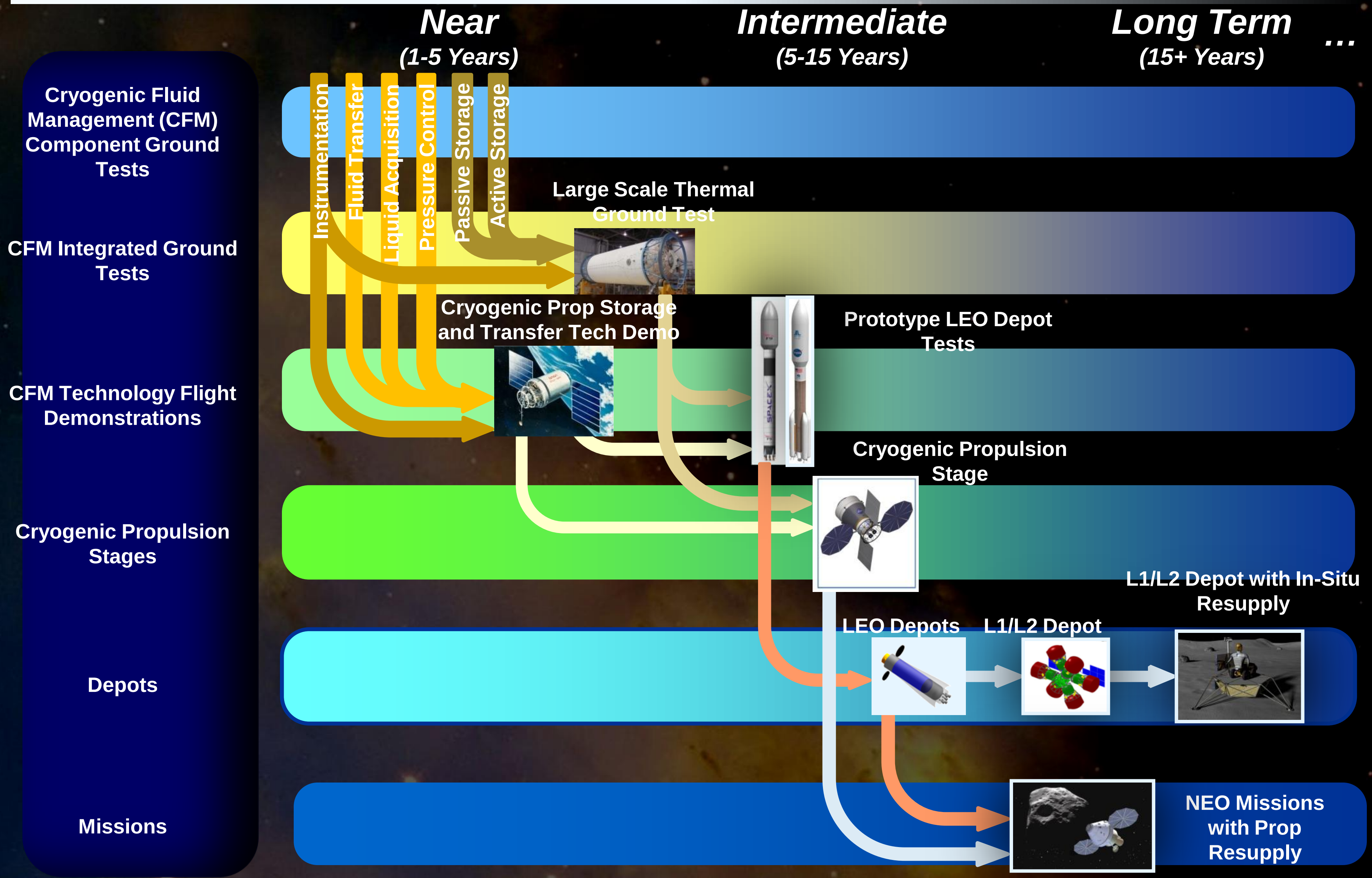
WWW.NASAWATCH.COM

Technology Roadmap Charts

WWW.NASAWATCH.COM

In-Space Propellant Resupply and Depot Technologies

WWW.NASAWATCH.COM



Near
(1-5 Years)

Intermediate
(5-15 Years)

Long Term
(15+ Years)

…

Cryogenic Fluid Management (CFM) Component Ground Tests

Instrumentation

Fluid Transfer

Liquid Acquisition

Pressure Control

Passive Storage

Active Storage

CFM Integrated Ground Tests

Large Scale Thermal Ground Test

CFM Technology Flight Demonstrations

Cryogenic Prop Storage and Transfer Tech Demo

Prototype LEO Depot Tests

Cryogenic Propulsion Stages

Cryogenic Propulsion Stage

Depots

LEO Depots

L1/L2 Depot

L1/L2 Depot with In-Situ Resupply

Missions

NEO Missions with Prop Resupply

WWW.NASAWATCH.COM

Background:
Four Necessary Conditions

Courtesy of Technology Applications Assessment Team

Four Necessary Conditions for a Cryogenic Depot:

NC1: Successfully demonstrate cryogenic liquid acquisition and quantity gauging. If you cannot acquire the liquid you cannot even start the fluid transfer process. You must also have an accurate method of determining how much liquid you have in the tank.

NC2: Successfully demonstrate the cryogenic fluid transfer process. Once you have demonstrated the ability to acquire vapor-free liquid, you then need to demonstrate that you can transfer the liquid and accumulate liquid in a receiver tank.

NC3: Successfully demonstrate the cryogenic fluid coupling. Steps 1 and 2 demonstrate the ability to move a cryogenic fluid between two tanks. Now you have to demonstrate the ability to move cryogenic fluid between two spacecraft.

NC4: Successfully demonstrate long-term thermal control. Steps 1 through 3 will allow for short-term cryogenic storage and transfer. The key to long-term storage is the ability to control the heat that reaches the cryogenic fluid.

WWW.NASAWATCH.COM

Top Level Depot Technologies (in priority order)

- Passive Storage*
  - Long term storage of cryogenic propellants is mandatory for depots
- Fluid Transfer
  - Only the simplest of concepts can be executed without fluid transfer
- Active Storage *
  - Active storage significantly enhances long term storage
- Liquid Acquisition *
  - Low gravity liquid acquisition augments depot capabilities by allowing the stored cryogens to be used for auxiliary propulsion and power, it also enables more efficient fluid transfer

* Also needed for the block II cryogenic propulsion stage

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Top Level Depot Technologies (cont'd.)

- Pressure Control and Pressurization*
  - Although very important to success, existing techniques used by current launch vehicles should be useable
- Instrumentation*
  - Good instrumentation is required for effective depot operation. Current launch vehicle instrumentation is adequate.
  - Accurate low gravity mass gauging could substantially reduce settling requirements

* Also needed for the block II cryogenic propulsion stage

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Other Technologies Identified

- Automated Rendezvous and Docking*
  - Already used on ISS and Demonstrated on Orbital Express, large fluid mass may prove challenging
- Micro-meteoroid Protection*
  - Very important to long term storage. Space Station technology is adequate but heavy
- Cryogenic Valves*
  - Cryogenic valve designs exist that will perform the required functions. Most launch vehicle cryogenic valves are helium actuated. Alternate actuators would reduce consumable usage.
- Subcooling/Densification
  - Can enhance storage times at the cost of ground handling complexity
- Para/Ortho Conversion
  - A good augmentation strategy for hydrogen vapor cooled shields
- Using boil-off for auxiliary propulsion and power
  - Good potential for Long Term depot
  - requires integrated testing

* Also needed for the block II cryogenic propulsion stage

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Summary

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Advantages

- Tens of billions of dollars of cost savings and lower up-front costs to fit within budget profile
- Allows first NEA/Lunar mission by 2024 using conservative budgets
- Launch every few months rather than once every 12-18 months
  - Provides experienced and focused workforce to improve safety
  - Operational learning for reduced costs and higher launch reliability.
- Allows multiple competitors for propellant delivery
  - Competition drives down costs
  - Alternatives available if critical launch failure occurs
  - Low-risk, hands-off way for international partners to contribute
- Reduced critical path mission complexity (AR&Ds, events, number of unique elements)
- Provides additional mission flexibility by variable propellant load
- Commonality with COTS/commercial/DoD vehicles will allow sharing of fixed costs between programs and “right-sized” vehicle for ISS
- Stimulate US commercial launch industry
- Reduces multi-payload manifesting integration issues

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Issues

- Congressional language
- Requires longer storage of cryo propellants than alternatives and addition of zero-g transfer technologies
- Volume/mass constraints (e.g, fairing size)
- NASA loses some control/oversight
- Added complexity of common CPS/depot
- Launch capacity build-up
- Aligning LEO departure plane with departure asymptote location for small NEA departure windows given LAN precession

WWW.NASAWATCH.COM

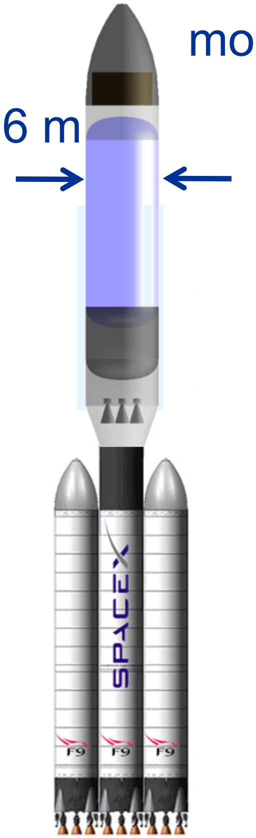
WWW.NASAWATCH.COM

Historical Example of Large Fairing

Titan 4B

- Fairing Length, 26.2 m
- Fairing diameter, 5.09 m
- Core Stage dia., 3.05 m
- ***Ratio of diameters, 1.67***

- Potential Fairing Diameters
  - SpaceX Falcon Heavy
    - Dia = 1.67 X 3.6 m = 6.0 m
  - ULA Delta IV/Atlas 5 Phase 2
    - Dia = 1.67 X 5.0 m = 8.35 m



Falcon Heavy fairing mod

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

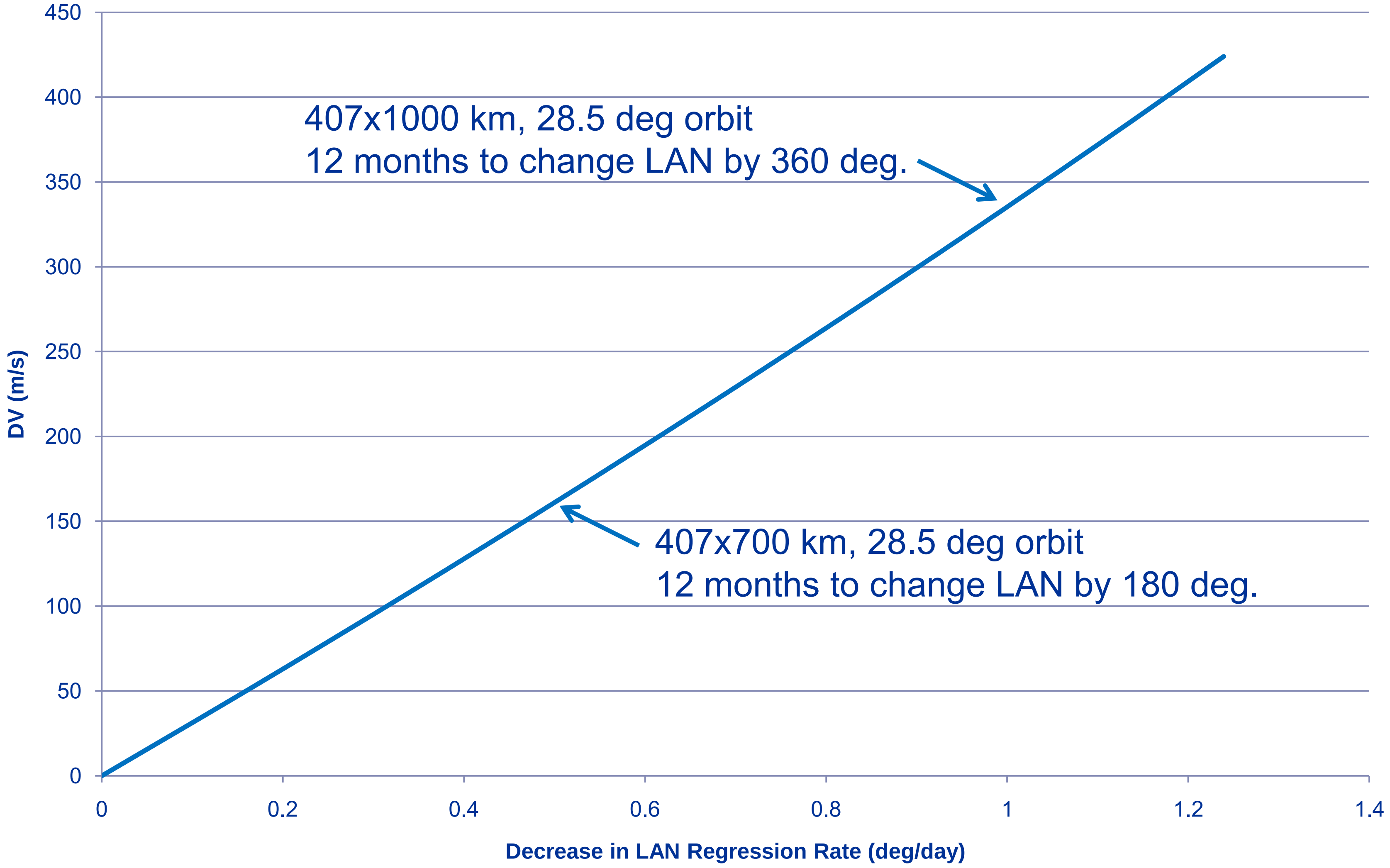
Launch Rate and Capacity Issues

- **Propellant depot options eliminated during HEFT 1 because of supposed launch capacity constraints**
- **Current US and world-wide launch vehicles operating significantly under-capacity**
  - Average launch rate for each major LV family is only 2.2/year..
- **Possible future LV capacity constraints is only an issue in the short term. Given a few years to invest, capacity is not a long-term problem.**
- **Additional capacity is a "feature", not a "bug", for US launch industry**
- **Current launch capabilities:**
  - Atlas V: 5-9/year. Could be doubled with modest infrastructure investment, and doubled again with additional infrastructure investments (e.g., Build a second VIF. ULA inputs at NASA HQ, 10/2010).
  - Delta IV: 2-5/year. Could be doubled with modest infrastructure investment, and doubled again with additional infrastructure investments (e.g., Second launch pad, ULA inputs at NASA HQ, 10/2010).
  - Falcon: 20/year by 2015, including 10 heavy, 12 already under contract, additional pads planned at WTR and ETR, less than $70M each (Musk E-Mail, Feb 2011)
  - Taurus II: : 6-12/year by 2015. (Claybaugh E-Mail, March 2011)
  - SeaLaunch: 5/year. Coming back on line. Capacity could be doubled with moderate infrastructure.
  - International partners (Ariane 5, H-II, Proton, Soyuz, Zenit, GSLV): More than 21/year for Ariane 5 & Proton alone

WWW.NASAWATCH.COM

WWW.NASAWATCH.COM

Changing LAN Regression Rate



WWW.NASAWATCH.COM

Forward Work

- Perform apples-to-apples LCC comparison once HAT completes costs
- Refine depot/CPS mass/performance, consistent with CPS Block 2
- Examine COTS-like procurement for launchers and tankers
- Examine possibility of commercial depot procurement/operation
- Determine risk/LOM and compare with HAT non-depot approach
- Determine “right-size” (mass/diameter) depot/CPS for multi-mission architecture (balance lunar, L1, Mars, NEA requirements)
- Trade location of depot (LEO, HEO, L1)
- Trade depot vs. stage refueling
- Trade common CPS/Depot with modular depot (e.g., Boeing)
- Compare baseline approach with triple-core HLLV (e.g., Falcon/EELV-derived) with single (30-50 mT) core developed first and used in conjunction with depot until need triple core for human Mars
  - Provides phased HLLV capability to fit within budget
  - Uses large Merlin 2-like hydrocarbon engines
  - Potentially procured using other transaction authority

WWW.NASAWATCH.COM

Advantages of Propellant Depot over Refueling

- Most expensive hardware/capability can be located on the depot to be re-used over and over again rather than be expended every flight
- The expendable CPS and delivery tankers can be made as dumb/cheap as possible
- Mass of the CPS that has to be pushed through thousands of m/s of delta-V can be reduced
- All of the important and costly avionic/software/IVHM can be on the depot
- The prox-ops and rendevous and docking systems can be on the depot, rather than on CPS
- The depot could do the last prox-ops maneuvers and even berth the tanker/CPS with an RMS
- Relieves CPS of need for active boil-off control for cis-lunar missions with few burns (Injection burns are made shortly after undocking. For NEO missions that need burns after 100 days of travel, this could be done by storables or cryo tanks inside of the main tanks and conditioned via passive systems and/or fuel cells)
- Reduces risk to CPS from MMOD by reducing required time in orbit prior to departure
- Reduces number of rendezvous events required to fuel CPS from many to one, reducing risk of collision or propellant transfer failure
- Reduces risk of LOM by decoupling propellant delivery flights from delivery of mission elements (i.e., elements stay on the ground until needed for mission)
- Opens the possibility to add other in-space services (e.g., maintenance and repair)
- Potential for multiple customers and creation of new commercial industry

WWW.NASAWATCH.COM