Propellant Depot Requirements Study Status Report

HAT Technical Interchange Meeting

July 21, 2011
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
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
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
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
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.
NEA Missions With Depot/CPS
Using Falcon Heavy LV
Full Capability, High Energy NEA (2008EV5) with SEP

NEA

- 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)

E-M L1

- 392 d Transit
- LEO 407 km x 407 km
- Block 2 CPS 1
- Circ burn by CPS 1 ΔV = 0.204 km/s
- SM kick stage
- SEP 1
- Kick Stage
- SEP 2
- Block 1 CPS 2
- Circ burn by Kick Stage ΔV = 0.204 km/s
- Circ burn by CPS 2 ΔV = 0.204 km/s
- Block 2 CPS 2
- Circ burn by CPS 2 ΔV = 0.204 km/s
- SEV
- EDL
- Earth Return VEI 11.8 km/s

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

NEA

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

407 km
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. Instrumentation | 32
11. Communication | 97
12. Thermal Control | 2,193
16. Range Safety and Abort | 69
16a. Mass Growth Allowance | 4,212
19. Ordnance | 20
Dry Mass | 18,252

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.
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

CBRS Characteristics:

- He @ 400 PSI & 100K
- Capillary tubing bonded to tank
- Capillary tubing on foil shield, at 20$^{th}$ layer of MLI
- Reservoir
- Circulator
- Tank struts
- Inner MLI
- Outer MLI
- LOX Tank
- LH$_2$ Tank
- Cryo Cooler
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 without 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
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

NEA via Depot, Number of Launches, Single Provider Scenario

- TBD Commercial Crew
- Falcon Heavy (MPCV)
- Falcon Heavy (DSH+SEV)
- Falcon Heavy (CPS)
- Falcon Heavy (Propellant)
- Falcon Heavy (Depot)
Falcon Heavy Propellant Tanker Design

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.

<table>
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<th>Item</th>
<th>Mass, kg</th>
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<td>5. Main Propulsion</td>
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<td>7. Prime Power</td>
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<td>9. Guidance and Navigation</td>
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<td>12. Thermal Control</td>
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<td>16. Range Safety and Abort</td>
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<td>16a. Mass Growth Allowance</td>
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<td>23. Inflight Losses</td>
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<tr>
<td>25. Total Propellant inc Boiloff</td>
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**Dry Mass** 5,106

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

- Depot R&D and Demo. NREC.
- CPS NREC.
- Propellant Depot Replace@End Life NREC.
- Exploration Elements Launcher(s) NREC.
- CPS REC.
- Propellant Depot NREC.
- Falcon Heavy-PSV NREC.
- Exploration Elements Launcher(s) REC.
- Falcon Heavy-PSV REC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) NREC.
- Deep Space Habitat DSH NREC.
- Deep Space Habitat DSH REC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) REC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) NREC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) REC.
- Project Insight/Oversight
- Program Integration
- Mission/Flight Ops + Ground/Launch Ops
- Commercial Crew Launch
- Alternate Blackline

$64B$ (2012-2030)
HEFT 1, DRM 4, NEA Mission in 2029

143B$ (2012-2030)
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)
Lunar Missions With Depot/CPS, Using Falcon Heavy LV
Lunar Surface Sortie Mission - LOR/LOR

**MOON**

- **LEO 407 km x 407 km**
  - Circ burn by CPS 1 \( \Delta V = 0.204 \text{ km/s} \)
  - Block 1 CPS 1
- **100 km Low Lunar Orbit**
  - LOI by CPS 1 \( \Delta V = 1.155 \text{ km/s} \)
  - TLI by CPS 1 \( \Delta V = 3.276 \text{ km/s} \)
  - TLI by CPS 2 \( \Delta V = 3.276 \text{ km/s} \)
  - Circ burn by CPS 2 \( \Delta V = 0.204 \text{ km/s} \)
  - Block 1 CPS 2
  - MPCV with Crew
  - Ascent by Lander \( \Delta V = 1.968 \text{ km/s} \)
- **7 d at Moon**
  - Dock All Elements (crew transfer)
  - Plane Change Contingency by MPCV \( \Delta V = 0.129 \text{ km/s} \)
  - TCM burns by MPCV \( \Delta V = 0.011 \text{ km/s} \)
  - TEI burn by MPCV \( \Delta V = 1.350 \text{ km/s} \)
  - RPOD by MPCV \( \Delta V = 0.032 \text{ km/s} \)
  - 4 d Transit
  - 5 d Transit

**EARTH**

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

**Notes:**
- spacecraft icons are not to scale
- \( \Delta V \)'s include 5% FPR
- RCS burns not displayed in chart
- Not all discrete burns displayed
MOON

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

100 km Low Lunar Orbit

LEO 407 km x 407 km

Deliver Depot

Fill Depot

Fill CPS

CPS

MPCV

Lander

Commercial Crew

Note: spacecraft icons are not to scale
Lunar Propellant LO2/LH2 Depot/CPS

**DRM 33C Depot LOX/LH2**

<table>
<thead>
<tr>
<th>Propellants</th>
<th>LOX/LH2</th>
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<tbody>
<tr>
<td>Stage Diameter</td>
<td>6 m</td>
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<tr>
<td>Stage Length</td>
<td>16 m</td>
</tr>
<tr>
<td>Oxidizer Boiloff</td>
<td>0% / month</td>
</tr>
<tr>
<td>Fuel Boiloff</td>
<td>0.5% / month</td>
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<tr>
<td>Sub-orbital T/W</td>
<td>0.72</td>
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<tr>
<td>Orbital T/W</td>
<td>0.15</td>
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<tr>
<td>Power</td>
<td>2625 W</td>
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<tr>
<td>Cryocooler Power</td>
<td>1625 W</td>
</tr>
<tr>
<td>Mass Growth, %</td>
<td>30</td>
</tr>
<tr>
<td># Engines / Type</td>
<td>3 RL10 B-2</td>
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<tr>
<td>Engine Isp (100%)</td>
<td>464 sec</td>
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<tr>
<td>Mass, kg</td>
<td><strong>5,213</strong></td>
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</table>

| 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. Instrumentation | 32 |
| 11. Communication | 97 |
| 12. Thermal Control | 1,521 |
| 16. Range Safety and Abort | 69 |
| 16a. Mass Growth Allowance | 2,539 |
| 19. Ordnance | 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.
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.
Falcon Heavy Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years

- Falcon Heavy-PSV NREC.
- Lunar Lander LO2/CH4 NREC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) NREC.
- Mission/Flight Ops + Ground/Launch Ops
- Program Integration
- HEFT I "Old Blackline"

60B$ (2012-2030)
**NEA**

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

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

- Deliver Depots
- Fill Depots
- Fill CPS
- Single CPS
- Jettison CPS
- SEV continues Operations at NEA

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

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NEA via Depot, Number of Launches, Single Provider Scenario

- TBD Commercial Crew
- Delta IV (SEV)
- Delta IV (MPCV)
- Delta IV (DSH)
- Delta IV (CPS)
- Delta IV (Propellant)
- Delta IV (Depot)
- Other Delta IV Business (Historical)
Delta IV Heavy Based NEA Mission LCC, First Mission 2024, Missions Every 3 Years

- Depot R&D and Demo. NREC.
- Exploration Elements Launcher(s) NREC.
- Exploration Elements Launcher(s) REC.
- Propellant Depot Replace@End Life
- CPS NREC
- Delta IV Heavy-PSV NREC.
- Delta IV Heavy-PSV REC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) NREC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) REC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT I) NREC.
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT I) REC.
- Deep Space Habitat DSH NREC.
- Deep Space Habitat DSH REC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) NREC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) REC.
- Project Insight/Oversight
- Mission/Flight Ops + Ground/Launch Ops
- Commercial Crew Launch
- Program Integration
- Alternate Blackline

$86B$ (2012-2030)
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
Lunar Missions With Depot/CPS, With Delta IV Heavy LV
**MOON**

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

**100 km Low Lunar Orbit**

**LEO 407 km x 407 km**

- Deliver Depot
- Fill Depot
- Fill CPS
- MPSV
- Lander
- Commercial Crew

**EARTH**

**Note:** spacecraft icons are not to scale
Lunar Mission Delta IV Heavy Launch Schedule

4 Lunar Missions / 36 Launches after Depot Placement

Lunar via depot, Number of launches, Single Provider Scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>TBD Commercial Crew</th>
<th>Delta IV (MPCV)</th>
<th>Delta IV (Lunar Lander)</th>
<th>Delta IV (CPS)</th>
<th>Delta IV (Propellant)</th>
<th>Delta IV (Depot)</th>
<th>Other Delta IV Business (Historical)</th>
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< Earlier Science Precursor Missions, or Exploration Element Test Flights - not shown.

Reserve propellant flights – not shown.
Delta IV Heavy Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years
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
NEA Missions With Depot/CPS, With Mixed Fleet of Falcon Heavy and Delta IV Heavy LVs
DRM 34B w/ Mixed Fleet + Propellant Depot/CPS

NEA

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

407 km

Deliver Depot

Fill Depot

Fill CPS

Earth

SEV continues Operations at NEA

Single Stage CPS

DSH

MPCV

MMSEV

Commercial Crew

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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.

### Graphs

- **Left Graph**: Number of Launches, NEA via Depot, TWO Providers Scenario
  - Delta IV (Propellant)
  - Other Delta IV Business (Historical)

- **Right Graph**: TBD Commercial Crew, Falcon Heavy (MPCV), Falcon Heavy (DSH+SEV), Falcon Heavy (CPS), Falcon Heavy (Propellant), Falcon Heavy (Depot)

### Notes
- Mixed Fleet Architecture – Separate infrastructure, supporting the same exploration missions
- Note! Other combinations possible.

- 3 NEA Missions / 36 Launches after Depot Placement
Delta IV & Falcon Heavy Mixed Fleet Based NEA Mission
LCC, First Mission 2024, Missions Every 3 Years

- Depot R&D and Demo. NREC.
- CPS REC.
- Exploration Elements Launcher(s) NREC.
- Falcon Heavy-PSV NREC.
- Delta IV Heavy-PSV REC.
- CPS NREC
- Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) REC.
- Deep Space Habitat DSH REC.
- Multi-Purpose Crew Vehicle (MPCV) (HEFT I) REC.
- Project Insight/Oversight
- Commercial Crew Launch
- Alternate Blackline

Propellant Depot NREC.
Exploration Elements Launcher(s) REC.
Delta IV Heavy-PSV NREC.
Propellant Depot Replace@End Life
Falcon Heavy-PSV REC.
Multi-Mission Space Exploration Vehicle (SEV) (HEFT II) NREC.
Deep Space Habitat DSH REC.
Multi-Purpose Crew Vehicle (MPCV) (HEFT I) NREC.
Mission/Flight Ops + Ground/Launch Ops
Program Integration
HEFT I "Old Blackline"

74B$ (2012-2030)
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
LO2/RP Depot/CPS Analysis Results
MOON

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

100 km Low Lunar Orbit

LEO 407 km x 407 km

Deliver Depot
Fill Depot
Fill Depot

LOI by Depot/CPS
$\Delta V = 0.846 \text{ km/s} + 0.050 \text{ km/s orbital maint.}$

TLI by Depot/CPS
$\Delta V = 3.127 \text{ km/s}$

Rendezvous & Circ by MPCV
$\Delta V = 0.035 \text{ km/s}$

Dock All Elements (crew transfer)

Descent by Lander
$\Delta V = 2.074 \text{ km/s}$

Ascent by Lander
$\Delta V = 1.974 \text{ km/s}$

Ascent Stage

Note: spacecraft icons are not to scale
**Lunar Propellant LO2/RP Depot/CPS**

**DRM33C LOX/RP**

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

**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.

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Body Structure</td>
<td>4,427</td>
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<tr>
<td>3. Induced Environmental Protection</td>
<td>247</td>
</tr>
<tr>
<td>5. Main Propulsion</td>
<td>1,464</td>
</tr>
<tr>
<td>6. Orient Control Separation</td>
<td>147</td>
</tr>
<tr>
<td>7. Prime Power</td>
<td>349</td>
</tr>
<tr>
<td>8. Power Conversion and Distribution</td>
<td>70</td>
</tr>
<tr>
<td>9. Guidance and Navigation</td>
<td>38</td>
</tr>
<tr>
<td>10. Instrumention</td>
<td>32</td>
</tr>
<tr>
<td>11. Communication</td>
<td>97</td>
</tr>
<tr>
<td>12. Thermal Control</td>
<td>1,417</td>
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<tr>
<td>16. Range Safety and Abort</td>
<td>69</td>
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<tr>
<td>16a. Mass Growth Allowance</td>
<td>2,513</td>
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<tr>
<td>19. Ordnance</td>
<td>20</td>
</tr>
<tr>
<td><strong>Dry Mass</strong></td>
<td><strong>10,890</strong></td>
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<tr>
<td>21. Residual Propellant</td>
<td>3,419</td>
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<td>23. Inflight Losses</td>
<td>22</td>
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<tr>
<td>25a. RCS Propellant</td>
<td>5,300</td>
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<td>25. Total Propellant inc Boiloff</td>
<td>170,968</td>
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<tr>
<td><strong>IMLEO</strong></td>
<td><strong>246,305</strong></td>
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<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<td>Payload Burn 1</td>
<td>55,706</td>
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<tr>
<td>DeltaV Burn 1</td>
<td>3,973</td>
</tr>
</tbody>
</table>
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

Number of Launches
Lunar via depot, Single Provider - "RP" Case
- TBD Commercial Crew
- Falcon Heavy (Lunar Lander+MPCV)
- Falcon Heavy (CPS)
- Falcon Heavy (Propellant)
- Falcon Heavy (Depot)
Falcon Heavy RP Based Lunar Mission LCC, First Mission 2024, Missions Every 2 Years
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
Integrated Launch Vehicle/Costs Sensitivity Results
NEA Mission (34B) Relative DDT&E Costs
Excluding Ground/Mission Ops and Oversight/Integration Costs

<table>
<thead>
<tr>
<th>Development Cost, 2011 $M</th>
<th>Falcon 9 Heavy 53 mt</th>
<th>Delta 4 Heavy 28 mt</th>
<th>Falcon 9 + 4 Mixed Fleet</th>
<th>Delta</th>
<th>F9H + 2xDDCPS Small</th>
<th>F9H + 2xRP-DCDPS Small</th>
<th>HLLV 100 mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$5,000</td>
<td>$10,000</td>
<td>$15,000</td>
<td>$20,000</td>
<td>$25,000</td>
<td>$30,000</td>
<td>$35,000</td>
</tr>
</tbody>
</table>

- HLLV 100 mt
- Kick Stage
- SEP
- CPS
- Delta 4 Heavy 28 mt
- Tanker on Delta 4 Heavy
- Falcon 9 Heavy 53 mt
- Tanker on Falcon 9 Heavy
- Depot/DDCPS Small-RP
- Depot/DDCPS Small
- Depot/DDCPS Large
- Commercial Crew Launch
- Lunar Lander
- Deep Space Hab
- MPCV
- MMSEV
NEA Mission (34B) Relative Mission Costs
Excluding Ground/Mission Ops and Oversight/Integration Costs
Lunar Mission (33C) Relative DDT&E Costs
Excluding Ground/Mission Ops and Oversight/Integration Costs

Development Cost 2011, $M

- Falcon 9 Heavy 53 mt
- Delta 4 Heavy 28 mt
- Falcon 9 + Delta 4 Mixed Fleet
- F9H + RP-DDCPS Small
- HLLV 100 mt

- HLLV 100 mt
- Kick Stage
- SEP
- Delta 4 Heavy 28mt
- Tanker in Delta 4 Heavy
- Falcon 9 Heavy 53mt
- Tanker in Falcon 9 Heavy
- Commercial Crew Launch
- Depot/DDCPS Small-RP
- Depot/DDCPS Small
- Depot/DDCPS Large
- CPS
- Lunar Lander
- Deep Space Hab
- MPCV
- MMSEV

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Lunar Mission (33C) Relative Mission Costs
Excluding Ground/Mission Ops and Oversight/Integration Costs

<table>
<thead>
<tr>
<th>Mission Element+Launch Cost, 2011 $M</th>
<th>Falcon 9 Heavy 53 mt</th>
<th>Delta 4 Heavy 28 mt</th>
<th>Falcon 9 + Delta 4 Mixed Fleet</th>
<th>F9H + RP-DDCPS Small</th>
<th>HLLV 100 mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Element</td>
<td>$0</td>
<td>$2,000</td>
<td>$4,000</td>
<td>$6,000</td>
<td>$8,000</td>
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<tr>
<td>Launch Cost</td>
<td>$10,000</td>
<td>$12,000</td>
<td>$10,000</td>
<td>$8,000</td>
<td>$6,000</td>
</tr>
</tbody>
</table>

Legend:
- HLLV 100 mt
- Kick Stage
- SEP
- Tanker in Delta 4 Heavy
- Tanker in Falcon 9 Heavy
- Falcon 9 Heavy 53mt
- Delta 4 Heavy 28mt
- Commercial Crew Launch
- Depot/DDCPS Small-RP
- Depot/DDCPS Small
- Depot/DDCPS Large
- CPS
- Lunar Lander
- Deep Space Hab
- MPCV
- MMSEV
Mission Risk and Availability Analysis
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)
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
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) - 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 results to the December 2010 HEFT II 34B DRM LOM 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)
Technology Roadmap Charts
In-Space Propellant Resupply and Depot Technologies

Near (1-5 Years)
- Cryogenic Fluid Management (CFM) Component Ground Tests
- CFM Integrated Ground Tests
- CFM Technology Flight Demonstrations
- Cryogenic Propulsion Stages
- Depots
- Missions
- Instrumentation
- Fluid Transfer
- Liquid Acquisition
- Pressure Control
- Passive Storage
- Active Storage
- Large Scale Thermal Ground Test
- Cryogenic Propulsion Stage
- Prototype LEO Depot Tests
- L1/L2 Depot with In-Situ Resupply
- LEO Depots
- L1/L2 Depot
- NEO Missions with Prop Resupply
Background:

Four Necessary Conditions

**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.
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
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
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
Summary
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
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
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 = $1.67 \times 3.6 \text{ m} = 6.0 \text{ m}$
  - ULA Delta IV/Atlas 5 Phase 2
    - Dia = $1.67 \times 5.0 \text{ m} = 8.35 \text{ m}$
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)
Changing LAN Regression Rate

407x1000 km, 28.5 deg orbit
12 months to change LAN by 360 deg.

407x700 km, 28.5 deg orbit
12 months to change LAN by 180 deg.
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
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 rendezvous 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.