Heavy Lift Launch for Lunar Exploration

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Lunar Transportation Requirements

• > 50 tonnes on lunar transfer trajectory
  – Apollo: 40 tonnes @ TLI for 2 men, 3 days on lunar surface.
  – Unlikely to be reduced significantly; can miniaturize components but not crew.
  – Maybe less if lunar oxygen is used for return propellant.
  – Note: 50 tonnes @ TLI implies 100 tonnes in LEO for 450 sec $I_{sp}$ LOX/LH$_2$ upper stage.
    • 70 tonnes if 850 sec nuclear thermal upper stage, but not likely in foreseeable political environment.

• Land anywhere on the Moon.
• Go any time of the month.
• Abort to Earth at any time.
Lunar Transportation System Architectures

- **Lunar Orbit Rendezvous (LOR)**
  - Heritage from Apollo; “mother ship” waits in orbit while specialized lunar lander makes trip to surface. Avoids “cost” of fuel to carry robust Earth-return vehicle on entire round trip.
  - Probably minimum LEO mass for basic lunar round trip, but still many tens of tonnes for mission “critical mass”.
  - Can go twice every day.
  - Limited to low lunar latitudes w/o sacrificing abort-to-Earth.
  - Return vehicle left in lunar orbit represents inefficient use of mass in a developed transportation system.
  - Potentially lengthy storage times for return vehicle in lunar orbit will require low-efficiency space storable propellants, or new technology for long-term cryo storage.
  - Possible basis of future system if/when extensive lunar orbit infrastructure is ultimately developed.
Transportation Architectures (cont.)

• **Earth Orbit Rendezvous (EOR)**
  
  – Required LEO mass is built up with multiple launches to rendezvous in Earth orbit.
  
  – Minimum launch can be a few tonnes to LEO, but many launches!
  
  – Perceived as a good match to space station infrastructure, but subtle issues result in significant operational problems.
    
    • Cryogenic fuel storage during build-up is challenging, particularly in event of missed launch window.
    
    • Limited launch windows; Earth-centered plane of “station” (or rendezvous) orbit *must* point to lunar targeting position at TLI.
      
      – Happens only once every 9 days for due-East 28.5° maximum performance orbit from Canaveral; less for 51.6° ISS orbit.
      
      – Less frequent windows if particular landing times must be selected (e.g., dawn) or avoided (e.g., midnight) at the Moon.
      
      – Similar constraints limit aborts if must also *return* to ISS.

  – Will become a “must” if multiple RLV payload modules are ultimately used to construct a lunar mission.
Transportation Architectures (cont.)

• Lunar Surface Rendezvous (LSR)
  – Required lunar mass attained with one or more launches to desired point(s) on lunar surface. Single mission must carry all essentials. (“Direct Ascent” in Apollo days.)
  – Ultimately necessary to build any sort of lunar base.
  – Can go twice per day, land anywhere, come home any time.
  – Minimum manned mission requires many tens of tonnes to maintain robust abort (propellant, heat shield), even assuming pre-deployment of surface assets.
    • Less if lunar-derived propellants available for return trip.
    • Cargo missions can be much smaller if economically favored.
    • Unavoidable penalties for carrying heat shield to lunar surface.
  – Obviously usable in concert with other methods, at cost of additional constraints.
Transportation Architectures (cont.)

• Lagrange Point Rendezvous (LPR)
  – Build space infrastructure at stable Lagrange Points (L4, L5) instead of/in addition to LEO; deploy to/from Earth/Moon.
    • 3 days from Earth, 2(?) days from Moon.
    • “Small” ΔV penalty for use of staging point.
    • Plenty of sunlight for power, plenty of shade for fuel storage.
    • Possibly best spot in cislunar space for “marshalling yard”.
  – Can come and go at any time to any place on either planetary surface.
  – Abort may not always be to Earth.
    • Potential problem in solar flare seasons.
  – Minimum manned mission from Earth still several tens of tonnes.
  – Probably more suitable for use as part of a well-developed cislunar infrastructure, rather than as an initial lunar return.
## Lunar Transportation Costs

### Benchmarks

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Cost($97)</th>
<th>LEO Payload (kg)</th>
<th>Cost/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturn V</td>
<td>$600 M*</td>
<td>140,000</td>
<td>4,300</td>
</tr>
<tr>
<td>Shuttle</td>
<td>$500 M**</td>
<td>23,000</td>
<td>22,000</td>
</tr>
<tr>
<td>Titan IV</td>
<td>$300 M</td>
<td>16,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Atlas II-AS</td>
<td>$130 M</td>
<td>8,600</td>
<td>15,000</td>
</tr>
<tr>
<td>Delta 7920</td>
<td>$50 M</td>
<td>5,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

### Goals

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Cost($97)</th>
<th>LEO Payload (kg)</th>
<th>Cost/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLV</td>
<td>$20 M</td>
<td>10,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Magnum</td>
<td>$160 M</td>
<td>80,000</td>
<td>2,000</td>
</tr>
</tbody>
</table>

* ≅ $100 M FY70$ for launch vehicle ($300 M for full Apollo mission).

** Very difficult to determine accurately; minimum $3 B to support a nominal 6 launches/year.
Transportation Architecture Summary

• All modes except EOR require a minimum manned mission of several tens of tonnes to TLI.
• EOR imposes numerous scheduling and operational constraints, and eliminates the economies of scale which are possible with larger payload envelopes.
• Robust lunar base development will require LSR no matter what else is done.
• History indicates that economies of scale produce significant cost/kg advantages for a heavy lifter.
• Conclusion: A heavy-lift launch vehicle is, if not strictly mandatory, highly desirable for lunar operations.
Heavy-Lift Launch Vehicle Concepts

- Numerous HLLV concept designs have been studied by NASA/DoD/Contractor teams for application to Lunar Return, Mars Exploration, and Ballistic Missile Defense applications.

<table>
<thead>
<tr>
<th>Vehicle/Heritage</th>
<th>LEO Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebuilt/Uprated Saturn V:</td>
<td>140+ tonnes</td>
</tr>
<tr>
<td>Saturn V derived:</td>
<td>240 tonnes</td>
</tr>
<tr>
<td>Shuttle-derived inline:</td>
<td>85 tonnes</td>
</tr>
<tr>
<td>Shuttle-derived sidemount:</td>
<td>80 tonnes</td>
</tr>
</tbody>
</table>
Apollo 17/Saturn V Rollout
Saturn V-Derived HLLV and ISS-Derived Habitat Module
Shuttle-Derived Sidemount Heavy Lift Launch Vehicle
Magnum Launch Vehicle - Potential Vehicle Paths

1. SDV Path
   - ET Diameter Tankage
     * Standard ET Fabrication
     * Non-performance Driven ET Fab
     * Extended Tank
     * Composites
   - Engine Options
     * RS-68
     * SSME w/ PA Mod
     * TRW Eng
     * RD-170
     * RD-171
     * RS-160
   - Booster Options
     * RS1B's
     * LR0's
     * Propellant Type
     * Engine Options
     * Pressure Fed
     * Hybrids
     * Titan IV Solids
   - US Options
     * Solid
     * Liquid
     * Storable
     * LOX/RP
     * LOX/LH2
     * Other?
     * Hybrid

2. Flyback Booster Path
   - Engine Options
     * RS-68
     * SSME w/ PA Mod
     * TRW Eng
     * RD-170
     * RD-171
     * RD-180
   - Flyback Booster Options
     * FBIR Concept from Parkinson / Early Study
   - US Options
     * Solid
     * Liquid
     * Storable
     * LOX/RP
     * LOX/LH2
     * Other?
     * Hybrid

3. Clean Sheet Path
   - Configuration
     * Selection
     * Parallel or Series
     * Propellant Selection
     * Engine Size and Number

4. Other Contractor Path
   - Lockheed Martin - Stellaris
   - Microcosm - Heavy Lift BMDO
   - Truax Engineering - Excalibur
   - Thiokol - EELV, Atlas, Delta Core w/ Solids
## SDV and LFBB Pathway Concepts
(Note: Cost and Performance Data are Very Preliminary)

<table>
<thead>
<tr>
<th>Concept Description</th>
<th>MLV - SDV-1a</th>
<th>MLV - SDV-1b</th>
<th>MLV - SDV-2</th>
<th>MLV - SDV-3</th>
<th>MLV - SDV-4</th>
<th>MLV w/ LFBB</th>
</tr>
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<tbody>
<tr>
<td>Preliminary</td>
<td>120 K</td>
<td>207 K</td>
<td>176 K</td>
<td>201 K</td>
<td>141 K</td>
<td>205 K</td>
</tr>
<tr>
<td>Performance</td>
<td>(220 x 220 nmi / 28°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDT&amp;E Cost</td>
<td>$1.46B</td>
<td>$1.46B</td>
<td>$2.26B</td>
<td>$2.00B</td>
<td>$2.41B</td>
<td>$1.46B</td>
</tr>
<tr>
<td>TFU</td>
<td>$279M</td>
<td>$359M</td>
<td>$294M</td>
<td>$494M</td>
<td>$669M</td>
<td>$225M</td>
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<tr>
<td>Average Unit Cost</td>
<td>$1917 / lb</td>
<td>$1488 / lb</td>
<td>$1347 / lb</td>
<td>$1761 / lb</td>
<td>$3553 / lb</td>
<td>$849 / lb</td>
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<tr>
<td>GLOW</td>
<td>4.62 Mlb</td>
<td>7.34 Mlb</td>
<td>4.70 Mlb</td>
<td>5.22 Mlb</td>
<td>7.11 Mlb</td>
<td>5.72 Mlb</td>
</tr>
</tbody>
</table>
What Does All This Cost, and What Might it Cost?

• It takes a lot of rocket to put a payload in low Earth orbit.
  – Typically 4-6 pounds of rocket hardware for each pound of satellite.
• Things tend to cost in proportion to what they weigh.
• Things tend to cost inversely according to the number made.
  – We build at most a few dozen rockets per year, at about $1000/lb.
• For an expendable vehicle, all of this expensive hardware gets thrown away after each use!
• A reusable system seems intuitively more economical, but an RLV requires even more rocket to put a payload in orbit.
  – Deorbit, TPS, and landing systems inevitably add mass.
  – While it doesn’t get “thrown away”, lifetime is still finite, and recurring costs are much higher; e.g. $16,000/lb for shuttle.
  – Initial development costs, hence amortization of these costs, will also be higher for an RLV.
What Does it Cost? (continued)

• It takes a long time and many people to prepare and launch a rocket.
  – The cost of reliability is very high; that of unreliability is even higher.
  – The “airline” approach to rocketry remains an elusive goal.

• Amortization of development costs is crucial for new vehicles.
  – X-15, STS non-recurring costs approximately FY99$100 K/lb.
  – Global flight rates for medium-class payloads (8-25 klbm) estimated to be no more than several dozen/year through 2020.
    • Optimistic assumption: ~20 flights/year captured by new vehicle.
  – “Cost of Money” mandates that commercial investments for development of a new vehicle must be returned within ~8 years.
    • An aggressive four-year development program implies ~4 years of flights to amortize any initial investment.
    • 30-40% minimum ROI required for “risky” investments.

• The price goes up when facility development, insurance, and profit are included.
Mathematical Model for Cost Analysis

• Assume the cost of the k-th launch to be composed of expended hardware, propellant, operations, and a share of development costs (Griffin & Claybaugh, 1996):

\[ C_k = C_h + C_p + C_o + C_{dk} \]

where

\[ C_h = \text{cost of expended hardware} \]
\[ C_p = \text{cost of propellant} \]
\[ C_o = \text{cost of launch operations, recovery, refurbishment} \]
\[ C_{dk} = \text{k-th launch share of vehicle development cost} \]

• Assume costs scale \textit{linearly} with, and depend \textit{only} upon, dry mass $M_s$.
  – Dependence only upon $M_s$ ignores complexity differences between vehicles (level of technology, stage integration, volume effects).
  – Linear assumption ignores potentially favorable returns-to-scale.

• Insurance and facility development costs neglected, but can be added.
Nomenclature

\(M_p\) = propellant mass
\(M_s\) = structural mass
\(R \equiv M_s / M_{PL} \equiv\) structural ratio
\(\eta = M_p / (M_p + M_s) =\) propellant mass fraction
\(c_h =\) specific cost of expended hardware (e.g., \$/lbm)
\(c_p =\) specific cost of propellant
\(c_L =\) hourly cost of labor (fully burdened)
\(c_d =\) specific launch vehicle development cost
\(f =\) mass fraction of expended hardware (1 for expendable)
\(L =\) labor intensity (man-hours/flight/vehicle-dry-mass)
\(g_k =\) development cost amortization fraction for k-th launch
Linear Launch Cost Model

• Given linear dependence on launch vehicle dry mass $M_s$, we find:

\[
C_h = c_h f M_s \\
C_p = c_p M_p = c_p \left( \frac{M_p}{M_s} \right) M_s = c_p \left( \frac{\eta}{(1-\eta)} \right) M_s \\
C_o = c_{L} L M_s \\
C_d = c_{d} g_k M_s
\]

• Total cost of $k$-th launch becomes

\[
C_k = c_h f M_s + c_p \left( \frac{\eta}{(1-\eta)} \right) M_s + c_{L} L M_s + c_{d} g_k M_s
\]

• Payload specific cost (e.g., cost per pound of payload) for $k$-th launch becomes

\[
c_k \equiv \frac{C_k}{M_{PL}} = R \left[ c_h f + c_p \frac{\eta}{(1-\eta)} + c_{L} L + c_{d} g_k \right]
\]
Structural Ratio

- Key performance parameter linking structural and propulsion technology with mission requirements (e.g., reference payload and orbit). For a single stage rocket, or an aggregated multistage vehicle with all burns to propellant depletion:

\[
R \equiv \frac{M_s}{M_{PL}} = \frac{(R^* - 1)}{[1/(1-\eta) - R^*]} = R(\eta, I_{sp}, \Delta V)
\]

where:
- \(I_{sp}\) = specific impulse
- \(R^* = \frac{M_i}{M_f} = e^{\Delta V/g_{Isp}}\) = mass ratio
- \(\Delta V\) = ideal velocity-to-be-gained
- \(M_i\) = initial mass
- \(M_f\) = final mass

- For the j-th stage of an N-stage rocket, \(R_j \equiv \frac{M_{sj}}{M_{PL}}\), and

\[
R = 1 + R_1 \ldots + R_j \ldots + R_N
\]

\[
R_j = \left[1 + \frac{R_{j+1}}{(1-\eta_{j+1})} + \ldots + \frac{R_N}{(1-\eta_N)}\right] \left(R_j^* - 1\right)/\left[1/(1-\eta_j) - R_j^*\right]
\]
Parameter Ranges for Existing Vehicles*

- $R = 2-6$ for expendables,
- $= 14$ for STS,
- $\approx 10-12$ for future single-stage-to-orbit (SSTO) RLV,
- $\approx 5$ for future two-stage-to-orbit (TSTO) RLV.
- $R\eta/(1-\eta) = 30-80$ for Atlas to STS
- $L = 4-20$ for Atlas, Delta, Titan-4, STS
- $c_p = \$0.5 - \$3/lb$ for lox RP to hypergols; $\approx \$0.25/lb$ for lox/hydrogen
- $c_h \approx \$1000/lb$ for expendables, $\$16,000$ for STS orbiter (FY95$)
- $c_L \approx \$100 K/\text{MY} = \$50/hr$
- $f = 1$ for expendables, $0.2-0.3$ for STS, $\approx 0.005(?)$ for future RLVs

*Transportation Systems Data Book, NASA-MSFC, DR-8, 2/15/93
ELV Marginal Launch Cost Example

• As a sanity check, let’s assume we have an existing fully-amortized vehicle (no development cost payback) with the following characteristics:

\[ R \approx 5 \text{ (typical two-stage expendable)} \]
\[ L \approx 4 \text{ (industry best practice)} \]
\[ c_p \approx \$0.50/\text{lbm} \text{ (lox/RP)} \]
\[ c_h \approx \$1000/\text{lb} \text{ (hardware cost for typical expendable launcher)} \]
\[ c_L \approx \$50/\text{hr} \]
\[ \eta \approx 0.9 \]
\[ f = 1 \text{ (fully expendable)} \]

Then the *marginal* cost of a launch is:

\[
\begin{align*}
C_h/M_{PL} &= R c_h f &= 5000/\text{lb-payload} \\
C_p/M_{PL} &= R c_p \eta/(1-\eta) &= 20/\text{lb-payload} \\
C_o/M_{PL} &= R c_L L &= 1000/\text{lb-payload} \\
C/M_{PL} &= c &\approx \$6000/\text{lb-payload}
\end{align*}
\]
The Cost of Rocket Hardware - What Might it Be?

- Expendable rockets cost about $1000/lb and are made by the dozens.
- Airplanes cost $500-$1000/lb and are made by the 100s. (About 1300 B-747s exist.)
- Boats cost $50-$100/lb and are made by the thousands.
- Cars cost $5-$10/lb and are made by the hundreds of thousands.
- Conclusion:
  - Volume effects are more important than vehicle type.
  - Factor-of-two reduction in $c_h$ for rockets would be a major victory.
  - Factor-of ten-cost reduction is needed to retain expendability as an option for deep cuts in launch cost -- how likely is this?
    - “Big Dumb Booster” concept is probably named appropriately.
Operations Costs

• Currently, $L \approx 10 \text{ MH/flight/lb} \Rightarrow \text{industry average}$
• Assume for the sake of argument:
  \[ c = $1000/\text{lb-payload (desired launch cost)} \]
  \[ c_h = 0 \Rightarrow \text{We’re assuming the vehicle is free!} \]
  \[ R \approx 5 \text{ (typical expendable; also, reasonable TSTO RLV goal)} \]
  \[ c_L = $50/\text{hr} \]
  \[ \frac{R\eta}{(1-\eta)c_p} = $20/\text{lb-payload} \Rightarrow \text{propellant cost is negligible} \]
• Then the launch cost is $RLc_L = $1000/\text{lb-payload}$, hence we require:

\[ L < 4 \text{ MH/flight/lb} = \text{Current best domestic practice!} \]

• A factor-of-ten improvement in $c$ to $100/\text{lb}$ would require $L < 0.4$!
  – Still assumes a free vehicle.
  – $20/\text{lb}$ propellant cost not negligible at this level.
• Question: Can we work much more efficiently than we do now?
• Answer: Maybe.
Summary of X-15 Operations

• 10 years (1959-1968)
• 350 people
• 3 vehicles (plus care and feeding of two B-52s)
• 199 flights
• 15,000 lbs (dry)
• 1 fatality

• Thus, $L \approx 0.8$ for the X-15 reusable vehicle program.
  – Factor of five better than current U.S. best practice, and on a government program, no less!

• Recent data (Claybaugh, 2000) indicate $L \approx 0.8$ also for Ariane
• Contrast with $L < 0.001$ for airlines, attained over thousands of flights using vehicles that last for decades.
• Assume TSTO RLV design with 40 klbm payload to due East 100 nmi orbit:

R = 5  (Orbital STAS RLV goal; range is 2-6 for TSTO expendables.)
\( \eta = 0.9 \) (Orbital STAS RLV goal)
\( f = 0.005 \)  (200 flights before replacement)
\( L = 1 \) mh/flight/lbm (~ 0.8 for X-15, Ariane; Claybaugh, 2000)
\( c_d = $15,000/lbm \) (average of X-33, X-34; Claybaugh, 2000)
\( c_h = $2,000/lbm \) (average of X-33, X-34; Claybaugh, 2000)
\( c_p = $0.25/lbm \) (LOX/LH\(_2\))
\( c_L = $50/hr \) (burdened labor)
\( g_k = 0.0125 \)  (straight-line amortization, 20 flights/year, 4 years)

(Unreasonably optimistic?)
RLV Launch Cost Example (cont.)

- Obtain
  
  \[
  \begin{align*}
  C_d/M_{PL} & = R_{g_k}c_d & = 940/\text{lb-payload} \\
  C_h/M_{PL} & = R_{c_h}f & = 50/\text{lb-payload} \\
  C_p/M_{PL} & = R_{c_p}\eta/(1-\eta) & = 10/\text{lb-payload} \\
  C_o/M_{PL} & = R_{c_L}L & = 250/\text{lb-payload} \\
  C/ M_{PL} & = c & = 1250/\text{lb-payload} \quad ($310 \text{ marginal cost})
  \end{align*}
  \]

- Even with best-case assumptions, operations cost dominates marginal launch cost. \( L = 4 \) (industry average) gives $1000/\text{lb-payload} marginal cost for processing labor alone.

- Hardware replacement costs relatively unimportant if X-33/X-34 trends are representative; 100 flight lifetime still gives $360/\text{lb-payload} marginal cost.
  
  - STS recurring cost (~$16,000/lb) yields $660/\text{lb-payload} marginal cost.

- Development cost amortization dominates early usage. If shuttle processes \( (c_d = 105 \text{ K/lbm}) \) are used, \( c = 7000/\text{lb-payload} \) for first 80 flights. Even B777 track record \( (c_d = 25 \text{ K/lbm}) \) is prohibitive, with \( c = 1900/\text{lb-payload} \) for first 80 flights.
RLV Cost Example (cont.)

- Fewer flights or delayed returns over payback period will yield even higher development cost contribution on initial flights.
  - But, a sustained program of lunar activity is one of the few things that might generate the requisite number of flights.
- Insurance and facility development costs have been omitted.
- The above results reflect cost only. Pricing to allow characteristic ROI for risky ventures (> 30%) can make new RLVs non-competitive against existing expendables, hence commercially unfungible.
- Conclusions:
  - X-33/X-34 development costs, while favorable compared to earlier systems such as X-15 or shuttle, are probably the acceptable ceiling if space launch cost is to be lowered via development of new commercial RLVs. Conventional development paradigms are not an option.
  - Government sponsorship is probably required.
    - Can we really expect man-rated RLV development at X-33/X-34 prices?
  - Even industry best-case operational efficiency is woefully poor.
HLLV Launch Cost Example

Let’s now assume an expendable HLLV TSTO design with 200 klbm payload to due East 100 nmi orbit, and consider the marginal cost:

\[ R = 1.8 \]  (Saturn V:  \( R = 1.83 \) for Stages 1 & 2, with 100 ton Skylab.)
\[ \eta = 0.93 \]  (Saturn V:  \( \eta_1 = 0.94, \eta_2 = 0.93 \))
\[ f = 1 \]
\[ L = 1 \text{ mh/flight/lbm} \] (same goal as for RLV example)
\[ c_d = 0 \]  (Government sponsored development, no amortization.)
\[ c_h = $500/\text{lbm} \]  (Factor of two improvement over present practice.)
\[ c_p = $0.25/\text{lbm} \]  (LOX/LH\(_2\); LOX/RP-1 is even cheaper.)
\[ c_L = $50/\text{hr} \]  (burdened labor)
\[ g_k = 0 \]
HLLV Launch Cost Example (cont.)

• Obtain

\[
\begin{align*}
C_h / M_{PL} &= R_c h f &= $900/lb-payload \\
C_p / M_{PL} &= R_c p \eta / (1-\eta) &= 6/lb-payload \\
C_o / M_{PL} &= R_c L L &= 250/lb-payload \\
C / M_{PL} &= c &= $1156/lb-payload
\end{align*}
\]

• Better than Saturn V mostly because of hardware production assumptions.

• Comparable to commercially-developed RLV with optimistic amortization model.
  – But not nearly as good as a fully-amortized RLV, such as might be assumed for a high-traffic lunar enterprise model.

• Even with favorable assumptions on production cost, and ignoring development cost, the cost of expended hardware dominates.
  – But only if we can get operations efficiency on par with X-15, Ariane.

• Conclusion: Expendable HLLV best for early, low-traffic lunar return.
  – RLV favored in the context of a high-traffic (e.g., 20+ launches/year) model.