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 anwhere , 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**

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

- **Goals**

RLV	$20 M	10,000	2,000
Magnum	$160 M	80,000	2,000

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* ≅ $100 M FY70$ 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

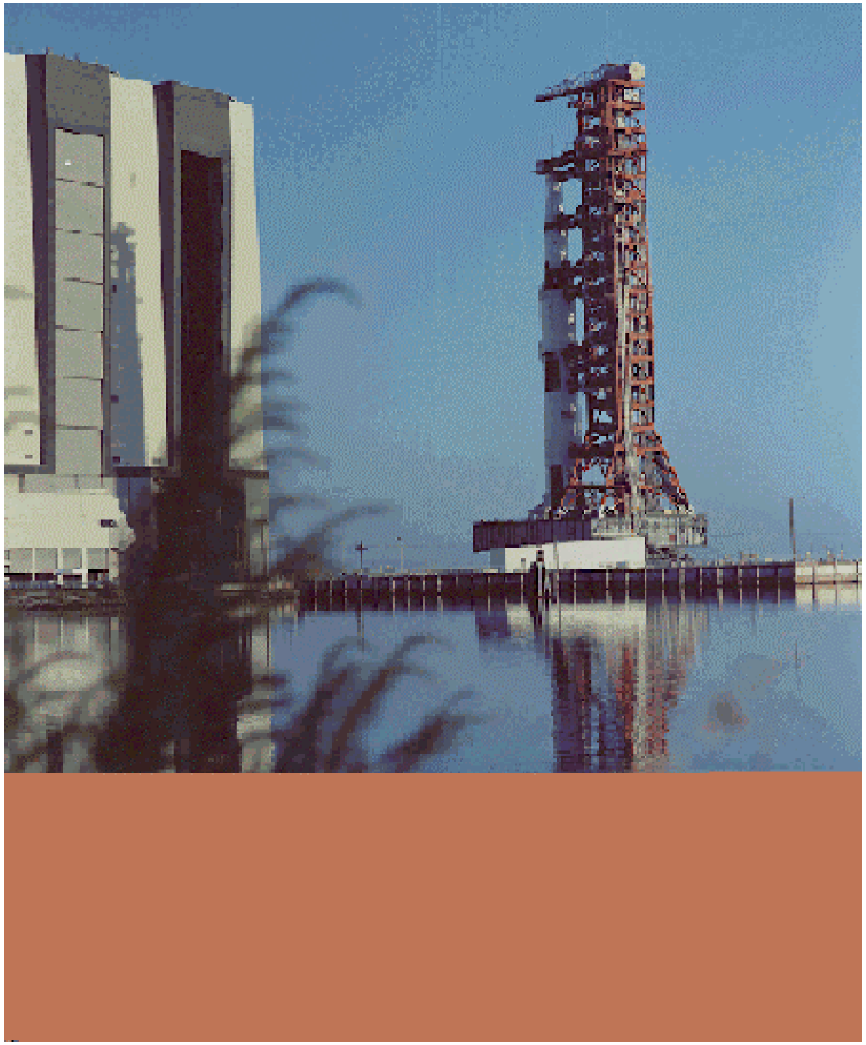
- **All modes except EOR require a minimum manned mission of several tens of tonnes to TLI.**
- **EOR imposes numerous scheduling and operational constraints, and eliminates the economies of scale which are possible with larger payload envelopes.**
- **Robust lunar base development will require LSR no 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.**

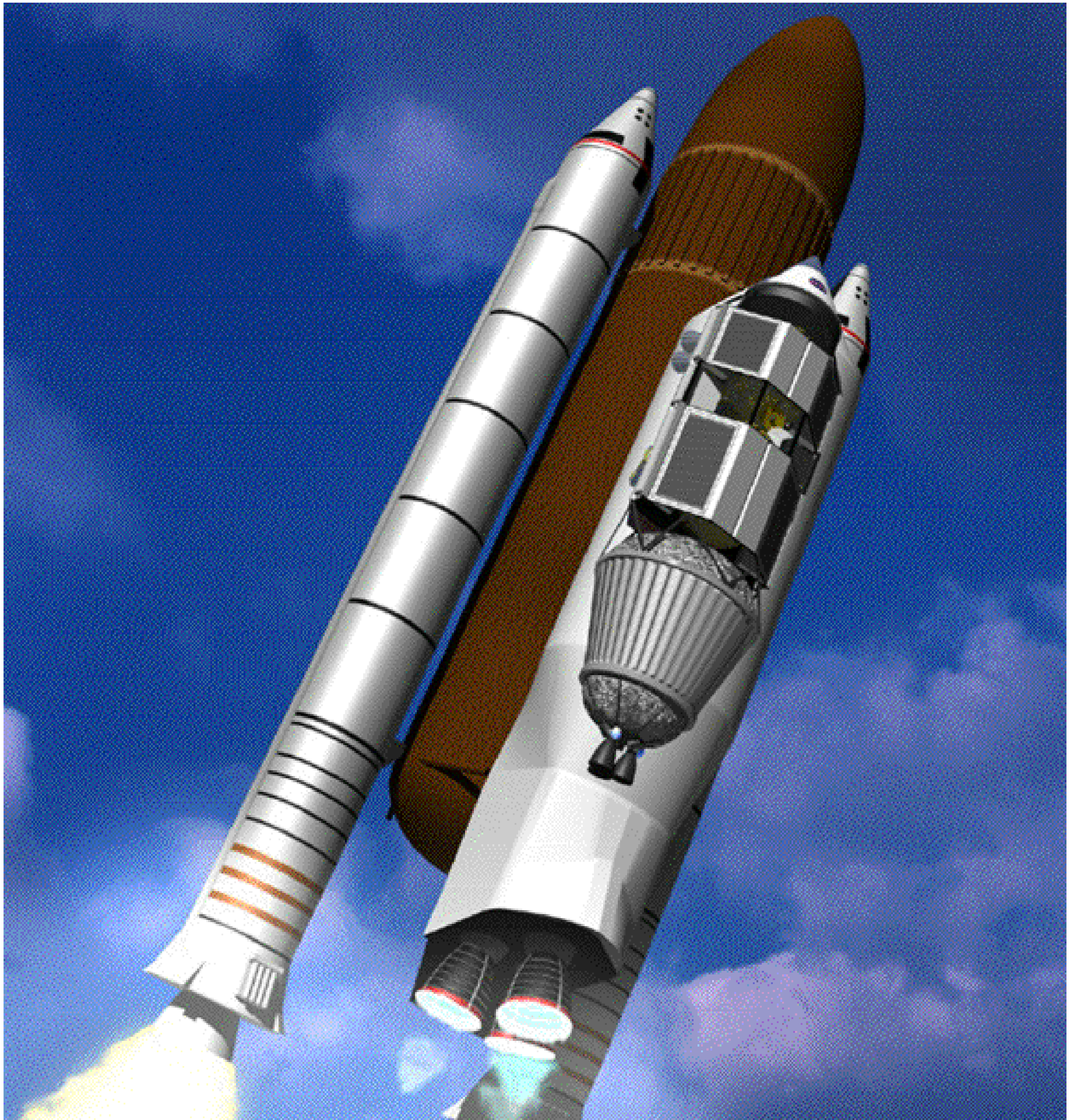
Vehicle/Heritage	LEO Payload
Rebuilt/Uprated Saturn V:	140+ tonnes
Saturn V derived:	240 tonnes
Shuttle-derived inline:	85 tonnes
Shuttle-derived sidemount:	80 tonnes

Apollo 17/Saturn V Rollout



Saturn V-Derived HLLV and ISS-Derived Habitat Module

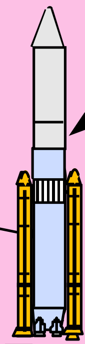
Shuttle-Derived Sidemount Heavy Lift Launch Vehicle



Magnum Launch Vehicle - Potential Vehicle Paths

①

SDV Path



US Options
- Solid
- Liquid
  - Storable
  - LOX/RP
  - LOX/LH2
  - Other?
- Hybrid

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
- RD-180

Booster Options
- RSRB's
- LRB's
  - Propellant Type
  - Engine Options
  - Pressure Fed
- Hybrids
- Titan IV Solids

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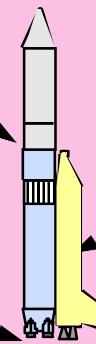
Flyback Booster Path



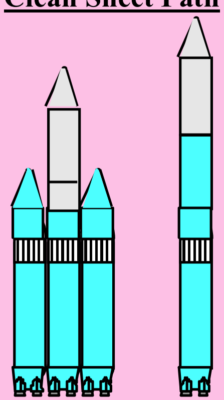
US Options
- Solid
- Liquid
  - Storable
  - LOX/RP
  - LOX/LH2
  - Other?
- Hybrid

Flyback Booster Options
- FBB Concept from Perkinson / Eudy Study

Engine Options
- RS-68
- SSME w/ PA Mod
- TRW Eng.
- RD-170
- RD-171
- RD-180

③

Clean Sheet Path



Configuration Selection
- Parallel or Series
- Propellant Selection
- Engine Size and Number

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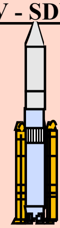
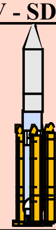
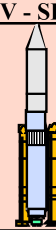
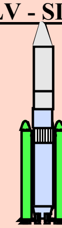
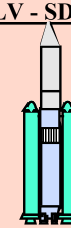
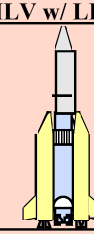
Other Contractor Path

- **Lockheed Martin - *Stellaris***
- **Microcosm - *Heavy Lift BMDO***
- **Truax Engineering - *Excalibur***
- **Thiokol - EELV, Atlas, Delta Core w/ Solids**

Magnum Launch Vehicle - Inhouse Concept Comparison

SDV and LFBB Pathway Concepts
(Note: Cost and Performance Data are Very Preliminary)

	MLV - SDV-1a 	**MLV - SDV-1b** 	**MLV - SDV-2** 	**MLV - SDV-3** 	**MLV - SDV-4** 	**MLV w/ LFBB** 	**Program Metric**
Concept Description	• **2 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	• **4 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 3 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp • Core Airstart @ T+100 sec • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	• **2 RSRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 P/A Modules - 2 SSME per P/A Module • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	• **2 Pump Fed LRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP - 3 - RD180 per LRB • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	• **2 Pressure Fed LRB's** • ET Dia. Core w/ 5 ft. Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP - 4 - 800K Pr-Fed Eng/LRB • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	• **2 Liq. Flyback Boosters** • ET Dia. Core, no Stretch • 2 Low Press / Low Cost Eng. - 650 Klb Thrust - 416s Isp - LOX / RP, 1.5Mlb each - RD180 type engs, 338s ISP • Kickstage for Circ. • Shroud w/ 25' x 92' Capacity	
Preliminary Performance (220 x 220 nmi @28°)	**120 K**	**207 K**	**176 K**	**201 K**	**141 K**	**205 K**	**175 K**
DDT&E Cost	**$1.46B**	**$1.46B**	**$2.26B**	**$2.00B**	**$2.41B**	**$1.46B** No LFBB DDTE	**$1.9B**
TFU	**$279M**	**$359M**	**$294M**	**$494M**	**$669M**	**$225M**	**N/A**
Average Unit Cost (over 25 flights)	**$1917 / lb** ($230M)	**$1488 / lb** ($308M)	**$1347 / lb** ($237M)	**$1761 / lb** ($354M)	**$3553 / lb** ($501M)	**$849 / lb** ($174M)	**$995 / lb LEO** ($176M / Flt.)
GLOW	**4.62 Mlb**	**7.34 Mlb**	**4.70 Mlb**	**5.22 Mlb**	**7.11 Mlb**	**5.72 Mlb**	**N/A**

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 = **cost of expended hardware**

C_p = **cost of propellant**

C_o = **cost of launch operations, recovery, refurbishment**

C_{dk} = **k-th launch share of vehicle development cost**

- **Assume costs scale *linearly* with, and depend *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:**

$$C_h = c_h f M_s$$
$$C_p = c_p M_p = c_p (M_p/M_s) M_s = c_p [\eta/(1-\eta)] M_s$$
$$C_o = c_L L M_s$$
$$C_d = c_d g_k M_s$$

- **Total cost of k-th launch becomes**

$$C_k = c_h f M_s + c_p[\eta/(1-\eta)] M_s + c_L L M_s + c_d g_k M_s$$

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

$$c_k \equiv C_k / M_{PL} = R [c_h f + c_p \eta/(1-\eta) + c_L L + c_d g_k]$$

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:**

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

where:

I_{sp} = **specific impulse**

$R^* = M_i/M_f = e^{\Delta V/gIsp}$ = **mass ratio**

ΔV = **ideal velocity-to-be-gained**

M_i = **initial mass**

M_f = **final mass**

- **For the j-th stage of an N-stage rocket,** $R_j \equiv M_{sj} / M_{PL}$, **and**

$$R = 1 + R_1 \ldots + R_j + \ldots + R_N$$

$$R_j = [1 + R_{j+1}/(1-\eta_{j+1}) + \ldots + R_N/(1-\eta_N)]\,(R_j^* - 1)/[1/(1-\eta_j) - R_j^*]$$

Parameter Ranges for Existing Vehicles*

- **R = 2-6 for expendables,**
- **= 14 for STS,**
- **≅ 10-12 for future single-stage-to-orbit (SSTO) RLV,**
- **≅ 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; ≅ \$0.25/lb for lox/hydrogen**
- **c_h ≅ \$1000/lb for expendables, \$16,000 for STS orbiter (FY95\$)**
- **c_L ≅ \$100 K/MY = \$50/hr**
- **f = 1 for expendables, 0.2-0.3 for STS, ≅ 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:

  $R \cong 5$ (typical two-stage expendable)

  $L \cong 4$ (industry best practice)

  $c_p \cong \$0.50$/lbm (lox/RP)

  $c_h \cong \$1000$/lb (hardware cost for typical expendable launcher)

  $c_L \cong \$50$/hr

  $\eta \cong 0.9$

  $f = 1$ (fully expendable)

  Then the *marginal* cost of a launch is:

$$C_h/M_{PL} = Rc_h f = 5000\text{/lb-payload}$$

$$C_p/M_{PL} = Rc_p \eta/(1-\eta) = 20\text{/lb-payload}$$

$$C_o/M_{PL} = Rc_L L = \underline{1000\text{/lb-payload}}$$

$$C/M_{PL} = c \cong \$6000\text{/lb-payload}$$

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, $L \cong 10$ MH/flight/lb => industry average**
- **Assume for the sake of argument:**

  c = \$1000/lb-payload (desired launch cost)

  $c_h = 0$ => We're assuming the vehicle is free!

  $R \cong 5$ (typical expendable; also, reasonable TSTO RLV goal)

  c_L = \$50/hr

  $R\eta/(1-\eta)c_p$ = \$20/lb-payload => propellant cost is negligible

- **Then the launch cost is RLc_L = \$1000/lb-payload, hence we require:**

  $L < 4$ MH/flight/lb = Current best domestic practice!

- **A factor-of-ten improvement in c to \$100/lb would require $L < 0.4$!**
  - **Still assumes a free vehicle.**
  - **\$20/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, $L \cong 0.8$ 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 $L \cong 0.8$ also for Ariane**
- **Contrast with $L < 0.001$ for airlines, attained over thousands of flights using vehicles that last for decades.**

RLV Launch Cost Example

- *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.)

η = 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**

C_d/M_{PL}	$= Rg_k c_d$	=	\$940/lb-payload
C_h/M_{PL}	$= Rc_h f$	=	50/lb-payload
C_p/M_{PL}	$= Rc_p \eta/(1-\eta)$	=	10/lb-payload
C_o/M_{PL}	$= Rc_L L$	=	<u>250/lb-payload</u>
C/M_{PL}	$= c$	=	\$1250/lb-payload (\$310 marginal cost)

- **Even with best-case assumptions, operations cost dominates marginal launch cost. L = 4 (industry average) gives \$1000/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/lb-payload *marginal* cost.**
  - **STS recurring cost (~\$16,000/lb) yields \$660/lb-payload marginal cost.**
- **Development cost amortization dominates early usage. If shuttle processes (c_d = \$105 K/lbm) are used, c = \$7000/lb-payload for first 80 flights. Even B777 track record (c_d = \$25 K/lbm) is prohibitive, with c = \$1900/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: $\eta_1 = 0.94$, $\eta_2 = 0.93$)

$f = 1$

$L = 1$ mh/flight/lbm (same goal as for RLV example)

$c_d = 0$ (Government sponsored development, no amortization.)

$c_h = \$500$/lbm (Factor of two improvement over present practice.)

$c_p = \$0.25$/lbm ($LOX/LH_2$; LOX/RP-1 is even cheaper.)

$c_L = \$50$/hr (burdened labor)

$g_k = 0$

HLLV Launch Cost Example (cont.)

- **Obtain**

$$
\begin{aligned}
C_h/M_{PL} &= Rc_h f &&= \$900\text{/lb-payload} \\
C_p/M_{PL} &= Rc_p \eta/(1-\eta) &&= 6\text{/lb-payload} \\
C_o/M_{PL} &= Rc_L L &&= \underline{250\text{/lb-payload}} \\
C/\, M_{PL} &= c &&= \$1156\text{/lb-payload}
\end{aligned}
$$

- **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.**